View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by CERN Document Server

Neutrinos

S.M. Bilenky
Joint Institute for Nuclear Research, Dubna, Russia,
and
Physik Department, Technische Universität München,
James-Franck-Strasse, D-85748 Garching bei München, Germany

Abstract

The general status of neutrino physics are given. The history of the neutrino, starting from Pauli and Fermi, is presented. The phenomenological V-A theory of the weak interaction and the unified theory of the weak and electromagnetic interactions, the so-called Standard Model, are discussed. The problems of of neutrino masses, neutrino mixing, and neutrino oscillations are discussed in some details.

Contents

1 Introduction **1**

2 The history of the neutrino. Pauli **3**

3 The first theory of β - decay. Fermi **4**

4 Lepton number. The Discovery of the neutrino **6**

5 Nonconservation of parity in β-decay. The two-component neutrino **8**

6 Universal current $\times$ current theory of weak interactions **11**

7 Discovery of the ν_μ. Electron and muon lepton numbers **15**

8 Strange particles in the current $\times$ current interaction. The Cabibbo angle **17**

9 Glashow-Weinberg-Salam theory of the electroweak interaction **20**

10 The discovery of neutral currents **22**

11 Deep inelastic neutrino-nucleon scattering and quark structure of the nucleon **24**

12 Neutrino masses. Introduction **28**

13 Discovery of the τ-lepton, b and t-quarks. The number of flavor neutrinos **29**

14 Neutrino mixing **30**

15 Neutrino oscillations **32**

16 Experiments on the search for neutrino oscillations **35**
16.1 The solar neutrino experiments 35
16.2 The atmospheric neutrino experiments 39
16.3 The LSND experiment 41

17 Neutrinoless double β-decay **42**

18 Neutrino masses from experiments on the measurement of the β-spectrum of tritium **43**

19 Conclusion **44**

1 Introduction

Neutrinos are elementary particles. Three flavor neutrinos exist in nature: the electron neutrino ν_e, the muon neutrino ν_μ and the tau neutrino ν_τ.

Neutrinos are members of the three lepton families. Other particles that are members of the families are, correspondingly,the electron e^-, the muon μ^- and the tau τ^-. There are also three families of other elementary particles, the quarks: (u, d), $(c\ , s)$ and (t, b)

There are three fundamental interactions of elementary particles that are characterized by the strength of the interaction: strong, electromagnetic and weak. There is also the fourth gravitational interaction between particles. However, it is so weak that it can be neglected at all available energies.

The strong interaction is the interaction between quarks and gluons, neutral particles with spin 1. The interaction between quarks is the result of the exchange of gluons. Protons, neutrons, pions and all other hadrons are bound states of quarks.

The electromagnetic interaction is the interaction between charged particles and γ -quanta. The Coulomb interaction between charged particles is due to the exchange of photons. Atoms of different elements are bound states of electrons and nuclei.

The weak interaction is the interaction between fundamental fermions (quarks, charged leptons, neutrinos) and charged $W^\pm$ and neutral Z^0 bosons, heavy particles with spin 1 . For example, the β-decay of the neutron

$$n \to p + e^- + \bar{\nu} \tag{1}$$

is due to the exchange of a charged W- boson between $e - \nu$ and $d - u$ pair in nucleons. Because of weak and electromagnetic interactions, all particles ,except the electron, proton and neutrinos are unstable. For example, the π^+-meson decays into μ^+ and ν_μ. The muon μ^+ decays into e^+ , $\bar{\nu}_\mu$ and ν_e and so on. It was established during the last thirty years that the weak and electromagnetic interactions are parts of a *electroweak interaction*

Quarks take part in strong, electromagnetic and weak interactions. Charged leptons - in electromagnetic and weak interactions. Neutrinos are exceptional elementary particles: their electric charge is equal to zero and they take part only in the weak interaction. The role of neutrinos in physics and astrophysics is determined by this fact.

The investigation of neutrino processes allows to one obtain important information on the structure of the weak interaction. The detailed study of the scattering of high energy neutrinos on nucleons was very important for the establishment of quark structure of the nucleons. The detection of solar neutrinos allows one to investigate the internal invisible region of the sun, where solar energy is produced etc.

Neutrinos are also exceptional particles because of their internal properties. The masses of the neutrinos are much smaller than the masses of the corresponding family partners. Because of small neutrino masses and the so called neutrino mixing new neutrino processes *neutrino oscillations* , periodical transitions between different flavor neutrinos, become possible. Recently evidence in favor of neutrino oscillations was found in the Super-Kamiokande experiment in Japan. This discovery and also the discovery of the deficit of solar neutrinos by the Homestake and other solar neutrino experiments opened a new field of research in neutrino physics: the physics of massive and mixed neutrinos. It is a general belief that neutrino masses and neutrino mixing angles are determined by new physics at a mass scale that is much larger than the scale of the present-day physics (hundreds of GeV).

We will list here the most important discoveries, connected with neutrinos.

1. In 1954-56 in the experiment of F. Reines and C.W. Cowan the electron neutrino was discovered. For this discovery F. Reines was rewarded by the Nobel prize in 1994.

2. In 1956 in the experiment of C.S. Wu et al the parity violation in β -decay was discovered.

3. In 1958 in the experiment of M. Goldhaber et al the helicity of the neutrino was measured and evidence for the left-handed two-component neutrino was obtained.

4. In 1962 in the Brookhaven experiment the second type of neutrino, the muon neutrino, was discovered. In 1988 for this discovery L.Lederman, J. Steinberger, and M. Schwartz were rewarded the Nobel prize for this discovery.

5. In 1973 in experiments at the neutrino beam at CERN a new type of weak interaction, Neutral Currents, was discovered.

6. In the eighties in experiments on the measurement of deep inelastic scattering of neutrinos on nucleons the quark structure of nucleons was revealed and established.

7. In 1970 in the experiment of R. Davis et al neutrinos from the sun were detected. In these experiments and also in the GALLEX, SAGE, Kamiokande and Super-Kamiokande solar neutrino experiments the existence of a solar neutrino problem (deficit of solar ν_e's) was discovered

8. In 1987, in the Kamiokande, IMB and Baksan experiments, neutrinos from the explosion of the Supernova SN1987A in the Large Magellanic Cloud were detected.

9. In 1998, in the Super-Kamiokande experiment, compelling evidence in favor of oscillations of atmospheric neutrinos was found.

10. ...

Here we present at an elementary level only the basics of neutrinos in particle physics. Those, who like to study this interesting and exciting field of physics must read the original papers and books. Some books and recent reviews are listed in the bibliography.

2 The history of the neutrino. Pauli

The history of the neutrino started in 1930 with the proposal of W. Pauli. At that time the electron e^- and proton p were considered as the only elementary particles. It was assumed that the nuclei of all elements heavier than hydrogen are bound states of electrons and protons.

In the framework of this assumption there were two fundamental problems. The first problem was connected with the spectrum of energies of electrons in β-decay, the process of the decay of a nucleus with emission of an electron. If some nucleus A is transferred into another nucleus A' with the emission of an electron then, according to the law of the conservation of the energy and momentum, the energy of the electron must be approximately equal to $M_A - M_{A'}$ (M_A and $M_{A'}$ are masses of the initial and final nucleus). However, in experiments on the investigation of β-decay a continuous spectrum of energies E up to $E_0 \simeq M_A - M_{A'}$ was observed.

The second problem was the problem of the spin of the nitrogen ${}^7N_{14}$ and other nuclei. The atomic number of ${}^7N_{14}$ is equal to 14 and the charge of the nucleus is equal to $7e$. If we assume that nuclei are bound states of protons and electrons, the ${}^7N_{14}$ nucleus is a bound state of 14 protons and 7 electrons. The spins of the proton and electron are equal to 1/2. Thus, for the spin of the ${}^7N_{14}$ nucleus we will obtain half-integer value. However, from experiments on the investigation of the spectrum of ${}^7N_{14}$ molecules it was known that ${}^7N_{14}$ nuclei satisfy Bose statistics and, according to the theorem on the connection between spin and statistics, the spin of the ${}^7N_{14}$ nucleus must be an integer. This problem was known as the "nitrogen catastrophe".

In order to solve these problems Pauli assumed that there exists in nature a neutral particle with spin 1/2, mass less than the electron mass and with a mean free path much larger than the mean free path of a photon. Pauli called this particle "neutron" and he assumed that not only p's and e's but also "neutron"'s are constituents of nuclei. This assumption allowed him to solve easily the problem of the spin of nitrogen and other nuclei. In fact, if in the $^{7}N_{14}$ nucleus there are an odd number of "neutrons" the spin of this nucleus will be an integer.

In order to explain β-spectra, Pauli assumed that in the process of β-decay the electron is emitted together with a "neutron" which is not detected in an experiment because of its large mean free path. The energy released in β -decay is shared between the electron and "neutron" and as a result the continuous spectrum of energies of electrons will be observed.

In 1932 the particle that today is called the neutron (the particle with a mass approximately equal to the mass of the proton and the spin equal to 1/2) was discovered by J. Chadwick in the nuclear reaction

$$^{4}\mathrm{He} + {}^{9}\mathrm{Be} \to {}^{12}\mathrm{C} + \mathrm{n} \qquad (2)$$

Soon after the discovery of the neutron, it was assumed independently by W. Heisenberg, E. Majorana and D. Ivanenko that the real constituents of nuclei are protons and neutrons. This assumption allowed to explain all existing nuclear data. In particular, according to this assumption the nucleus $^{7}N_{14}$ is a bound state of 7 protons and 7 neutrons and the spin of this nucleus must be an integer. Thus, the "nitrogen catastrophe" disappeared.

3 The first theory of β - decay. Fermi

In 1933-34 E. Fermi proposed the first theory of the β-decay of nuclei. The Fermi theory was based on the assumption that nuclei are bound states of protons and neutrons and on the Pauli hypothesis of the existence of a neutral, light, spin 1/2 particle with a large mean free path. Fermi baptized this particle with the name neutrino (from Italian neutral, small). Following Pauli, Fermi assumed that in β- decay the electron is emitted together with the neutrino. The problem was to understand how an electron-neutrino pair is emitted from a nucleus which is a bound state of protons and neutrons.

For Fermi it was important an analogy with electrodynamics. According to quantum electrodynamics in the transition of an electron from an excited state of an atom into a lower state a photon is emitted. In analogy with this process Fermi assumed that the electron-neutrino pair *is produced in the process of the quantum transition* of a neutron inside a nucleus into a proton

$$n \to p + e^{-} + \nu \qquad (3)$$

The first theory of β- decay was also built by Fermi in close analogy with quantum electrodynamics. The main quantity of the quantum field theory is the density of the energy of the interaction, that is called the Hamiltonian of the interaction.

The Hamiltonian of the electromagnetic interaction has the form of the scalar product of the electromagnetic current $j^{em}_\alpha(x)$ and the electromagnetic field $A^\alpha(x)$

$$\mathcal{H}^{\rm em}_I(x) = e\; j^{\rm em}_\alpha(x)\; A^\alpha(x) \tag{4}$$

where the sum over $\alpha = 0, 1, 2, 3$ is assumed. The electric charge e characterizes the strength of the electromagnetic interaction.

The electromagnetic current j^{em}_α is a 4-vector. The time component j^{em}_0 is the density of charge and the space components j^{em}_i (i=1,2,3) are components of the vector current. The electromagnetic field A^α is also a 4-vector: A^0 is a scalar potential and A^i are components of a vector potential.

The electromagnetic current of protons is given by

$$j^{\rm em}_\alpha(x) = \bar{p}(x)\gamma_\alpha p(x) \tag{5}$$

Here γ_α are the Dirac matrices and $p(x)$ is the proton field.

In analogy with (5) Fermi assumed that the Hamiltonian of β- decay had the form of the scalar product of the proton-neutron and electron-neutrino currents

$$\mathcal{H}^\beta_I = G_F(\bar{p}\gamma_\alpha n)(\bar{e}\gamma^\alpha\nu)\; +\; h.c. \tag{6}$$

Here G_F is the constant that characterize the strength of the β -decay interaction (G_F is called Fermi constant), $n(x)$ is the field of neutrons, $e(x)$ is the field of electrons and $\nu(x)$ is the field of neutrino.

In quantum field theory $n(x)$ is the operator which annihilates the neutron in the initial state, the operator $\bar{p}(x)$ creates the proton in the final state and the operators $\bar{e}(x)$ and $\nu(x)$ create the final electron and neutrino.

The Fermi theory allows one to describe the β- decay of different nuclei. This theory, however, could not describe all β- decay data. In 1936 Gamov and Teller generalized the Fermi theory by including in the Hamiltonian additional scalar, tensor, pseudovector and pseudoscalar terms with four additional interaction constants.

All β- decay data, existing at that time, could be described by the Fermi-Gamov-Teller interaction. This was an indirect evidence of the correctness of the Pauli-Fermi hypothesis of the neutrino. The direct proof of the existence of the neutrino was obtained only in the beginning of the fifties in the F. Reines and C.L. Cowan experiment. We will discuss this experiment in the next section. Let us start with a discussion of the notion of *lepton number* .

4 Lepton number. The Discovery of the neutrino

As is well known, the total electric charge is conserved. This means that only such processes are allowed in which the sums of the electric charges of the initial and final particles are equal.

According to quantum field theory every charged particle has its *antiparticle*, a particle with the same mass and spin but opposite charge. This general consequence of quantum field theory is confirmed by all existing experimental data. The antiparticle of the electron is the positron. The electron and the positron have the same mass and the same spin and the electric charges of the electron and positron are equal to $-e$ and e, respectively. The existence of the positron was predicted on the basis of the Dirac theory of the electron. The positron was discovered by C.D. Anderson in 1932. The antiparticle of the proton is the antiproton $\bar{p}$, a particle with electric charge equal to $-e$ and a mass equal to the proton mass. The antiproton was discovered in 1955 by O. Chamberlain, E.G. Segre et al. The antineutron $\bar{n}$ was discovered in 1956 and so on.

Except electric charge there exist other conserved charges. One such charge is the *baryon number*. The baryon numbers of p and $\bar{p}$ are equal to 1 and -1, respectively. The baryon numbers of the $\pi^{\pm}$ -mesons, $K^{\pm}$, γ-quantum and other bosons are equal to zero. Due to the conservation of the baryon number the proton is a stable particle.

Let us now return to the neutrino. The fact that the neutrino is produced in β-decay together with an electron suggests that there exist some conserved quantum number that characterizes these particles. This number is called lepton number. Let us assume that the lepton numbers of the electron and the neutrino are equal to 1 and lepton numbers of the proton, neutron, photon and other particles are equal to zero. According to the general theorem, we mentioned before, the lepton number of the positron is equal to -1 and the antineutrino, the particle with the lepton number equal to -1, must exist. From the conservation of lepton number it follows that in β-decay together with an electron an *antineutrino* is emitted. We will discuss later the experiment in which evidence in favor of conservation of lepton number was obtained.

Now we will consider the experiment of F. Reines and C.L. Cowan in which the (anti)neutrino was discovered. In this experiment antineutrinos that are produced in β-decays of different nuclei, products of the fission of U and Pu in a reactor, were detected via the observation of the process

$$\bar{\nu} + p \to e^{+} + n \tag{7}$$

A reactor is a very intense source of antineutrinos: about 2×10^{14} antineutrinos per second are emitted per kW, generated by the reactor. The power of a modern reactor is about 4 GW. Thus, about 10^{21} antineutrinos are emitted by a reactor per second. The experiment of Reines and Cowan was done at the Savannah River reactor in USA. The detector in this experiment was a liquid scintillator loaded with cadmium. The positron, produced in the process (7), quickly slowed down to rest and annihilated with an electron into two γ-quanta with energies about $E = m_e \simeq 0.51 MeV$, moving in opposite directions. These γ-quanta were detected by photomultipliers connected with scintillators.

The neutron produced in the process (7) was slowed down and was captured by a cadmium nucleus emitting γ-quanta with total energy about 9MeV. These

γ-quanta give a several microseconds delayed signal in the photomultipliers.

The probability of interaction is characterized in physics by the *cross section* that has dimension of (length)^2. In order to determine the cross section we will consider the flux of the particles that pass through the matter. Let us consider the element of the volume of the target with unit area oriented perpendicular to the momentum $\vec{p}$ (see Fig. 1) The number of particles of the target in this

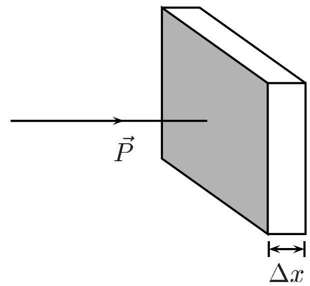


Figure 1: The element of the volume of the target oriented perpendicularly to the momentum $\vec{p}$.

volume is equal to $1 \cdot \Delta x \cdot \rho$ (ρ is the number density of the target). The cross section σ of a process of scattering, absorption,... is the probability of the process per one particle in the target and per unit flux. For the change of the flux after passing trough the element, shown in Fig. 1 we have

$$\Delta I(x) = I(x + \Delta x) - I(x) = -\rho\sigma\Delta x I(x) \tag{8}$$

From (8)we obtain

$$I(x) = e^{-\rho\sigma x} I(0) \tag{9}$$

where x is the distance that the particles pass in the matter. We can rewrite (9) in the form

$$I(x) = e^{-\frac{x}{L}} I(0) \tag{10}$$

where $L = \frac{1}{\rho\sigma}$ is the mean free path.

For the cross section of the process (7) in the experiment of Reines and Cowan the following value was found

$$\sigma = (11 \pm 4) \times 10^{-44}\ \mathrm{cm}^2 \tag{11}$$

This is a very small cross section. Let us consider the propagation of reactor antineutrinos with an energy of a few MeV in the earth. We have $\sigma \simeq 10^{-43}$ cm^2 and $\rho \simeq 10^{24}$ protons per cm^3. Thus, for the mean free path of a neutrino in the earth we have $L \simeq 10^{14}$ km. Remember that the earth's diameter is about 10^4 km. Thus, the probability for an antineutrino with an energy of a few MeV to interact with the matter of the earth is about 10^{-10}!

The fact that the neutrino and the antineutrino are different particles was established in the reactor experiment of R. Davis in 1955. As we discussed earlier, a reactor is a source of *antineutrinos*. If the lepton number is conserved, the reaction

$$\bar{\nu} + {}^{37}\mathrm{Cl} \to \mathrm{e}^- + {}^{37}\mathrm{Ar} \tag{12}$$

is forbidden. In the Davis experiment a large tank with carbon tetrachloride (C_2Cl_4) liquid was irradiated over a long period of time by antineutrinos from the reactor. After every run atoms of ^{37}Ar were extracted from the liquid by purging it with ${}^4He$ gas and they were put into a low-background Geiger counter. The γ-quanta produced in the e^- capture by ${}^{37}Ar$ were detected. No effect was observed. For the cross section of the process (12) it was found that

$$\sigma = (0.1 \pm 0.6) \times 10^{-45}\ \mathrm{cm}^2 \tag{13}$$

If the neutrino and the antineutrino had been identical, for the cross section of the process (12) the following value

$$\sigma = 2 \times 10^{-45}\ \mathrm{cm}^2 \tag{14}$$

would have been expected.

5 Nonconservation of parity in β-decay. The two-component neutrino

In 1956 in an experiment by C.S. Wu et al nonconservation of parity in β-decay was discovered. This was a very important discovery in particle physics that drastically changed our understanding of the weak interaction and the neutrino.

In order to explain the phenomenon of parity violation we must remember that there are two types of vectors : (true) vectors and pseudovectors. The direction of a vector does not depend on the choice of the coordinate system. The direction of a pseudovector is changed if we change the handedness of the coordinate system. Typical vectors are momentum, coordinate, electric field etc. Angular momentum, spin, magnetic field etc are pseudovectors.

Let us consider two coordinate systems: some right-handed system and a system with all axes directed opposite to the direction of the axes of the first system. The second system is left-handed one. If some vector $\vec{A}$ has components A_i (i=1,2,3) in the first system, in the second system the coordinates of this vector will be $-A_i$. If $\vec{B}$ is pseudovector with coordinates B_i in the first system, then in the second system its coordinates will be B_i (pseudovector changes direction). The transformation from the first system to the second one is called inversion or parity transformation.

In the Wu et al experiment the β-decay of polarized nuclei ${}^{60}Co$ nuclei was investigated. The polarization (the average value of the spin) is a pseudovector. Let us consider in a right-handed system the emission of an electron at an angle

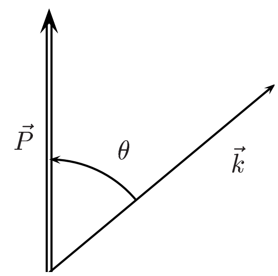


Figure 2: The emission of an electron with the momentum $\vec{k}$ by a nucleus with polarization $\vec{P}$ (right-handed system).

θ between the direction of the polarization of the nucleus and the electron momentum (see Fig. 2). In the left-handed system the direction of the polarization is reversed and Fig. 2 corresponds to the emission of an electron at an angle π - θ (see Fig. 3). The emission of an electron at the angle π - θ in the right-

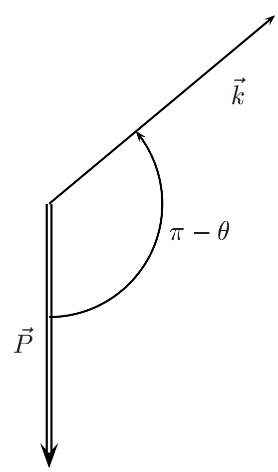


Figure 3: The same as in Fig. 2 but in the left-handed system.

handed system corresponds to the emission of an electron at the angle θ in the left-handed system. Thus, right-handed and left-handed systems are equivalent (the parity is conserved) if the number of electrons emitted (in a fixed system) at the angles θ and π - θ are equal.

In the experiment of Wu et al a large asymmetry of the emission of the electrons with respect to the polarization of the nuclei was discovered. It was observed that electrons are emitted predominantly in the direction opposite to the direction of the polarization of the nuclei. Thus, it was proved that parity is not conserved in β-decay (the left-handed and right-handed systems are not equivalent). Later it was shown that parity is not conserved in other weak processes.

Let us now consider in a right-handed system the emission of a left-handed neutrino ν_L, a neutrino with the projection of the spin on the direction of momentum (helicity) equal to -1 . In the left-handed system the projection of the spin on the vector of momentum of the neutrino will be equal to +1 (spin changes direction) . Thus, if parity is conserved the probabilities of emission of the left-handed neutrino ν_L and the right-handed neutrino ν_R (in a fixed system) must be the same:

$$w(\nu_L) = w(\nu_R) \tag{15}$$

The discovery of the nonconservation of parity in weak interactions means that these probabilities are not equal.

In 1957 Landau, Lee and Yang and Salam proposed the theory of the *two component neutrino*. This theory is based on the assumption that the mass of the neutrino is equal to zero. According to the theory of the two-component neutrino for the neutrino there are only two possibilities:

1. the neutrino is a left-handed particle ν_L and the antineutrino is a right-handed antiparticle $\bar{\nu}_R$;

2. the neutrino is a right-handed particle ν_R and the antineutrino is a left-handed antiparticle $\bar{\nu}_L$.

In both cases the equality (15) is violated maximally.

The helicity of the neutrino was measured in 1957 in a spectacular experiment by Goldhaber et al. In this experiment neutrinos were produced in the K-capture

$$\begin{array}{lll} e^- + \mathrm{Gd} \to \nu_{\mathrm{e}} + & \mathrm{Sm}^* & \\ & \downarrow & \\ & \mathrm{Sm} & + \gamma \end{array} \tag{16}$$

The measurement of the circular polarization of γ-quantum from the decay of Sm^* allowed to determine the helicity of the neutrino. The two-component neutrino theory was confirmed by this experiment and it was established that the neutrino is a particle with negative helicity. (see Fig. 4).

6 Universal current $\times$ current theory of weak interactions

The discovery of parity nonconservation in the weak interaction and the confirmation of the theory of a two-component neutrino led to an enormous progress in the development of the weak interaction theory (Feynman and Gell-Mann,

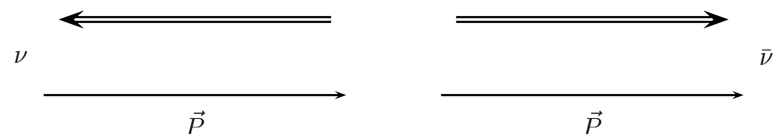


Figure 4: Helicities of two-component neutrino and antineutrino. The vector of the spin (momentum) of neutrino (antineutrino) is shown by double line (single line).

Marshak and Sudarshan 1958). At that time not only β-decay, but also other weak processes were known. One such processes is μ-capture

$$\mu^- + p \to \nu + n \tag{17}$$

The first idea of a possible interaction, responsible for the decay (17), was put forward by B.Pontecorvo. He compared the probabilities of μ-capture and K-capture of an electron by a nucleus and came to the conclusion that the corresponding interaction constants are of the same order. B. Pontecorvo assumed that there exists a *universal weak interaction* that includes e - ν and μ- ν pairs. The idea of μ - e universality was proposed also by G. Puppi, O.Klein and other authors.

Let us notice that any fermion field $\psi(x)$ can be presented as a sum of a left-handed component $\psi_L(x)$ and a right-handed component $\psi_R(x)$

$$\psi(x) = \psi_L(x) + \psi_R(x) \tag{18}$$

where

$$\psi_{L,R}(x) = \frac{1 \mp \gamma_5}{2}\ \psi(x) \tag{19}$$

and γ_5 is a Dirac matrix.

The fact that the neutrino is a particle with negative helicity means that the field of a neutrino is a left-handed field ν_L. Feynman and Gell-Mann, Marshak and Sudarshan assumed that in the Hamiltonian of the weak interactions enter *left-handed components of all fields.* If we will make this assumption the Hamiltonian of β-decay takes the very simple form

$$\mathcal{H}_I^\beta = \frac{G_{\mathrm{F}}}{\sqrt{2}}\ 4\ (\bar{p}_L \gamma^\alpha \nu_L)(\bar{e}_L \gamma_\alpha \nu_L)\ +\ h.c. \tag{20}$$

This interaction, like the Fermi interaction, is characterized by only one interaction constant G_F. It contains, however, parity-conserving (vector $\times$ vector and axial $\times$ axial) and parity-violating (vector $\times$ axial and axial $\times$ vector) parts.

Assuming $\mu - e$ universality, Feynman and Gell-Mann proposed the theory that allowed one to describe all the weak processes known at that time and to predict new weak processes. They assumed that there exists a *weak current*

$$j^\alpha = 2\ [\bar{p}_L \gamma^\alpha n_L\ +\ \bar{\nu}_{eL} \gamma^\alpha e_L\ +\ \bar{\nu}_{\mu L} \gamma^\alpha \mu_L] \tag{21}$$

and that the Hamiltonian of the weak interaction has the simple current × current form

$$\mathcal{H}_I = \frac{G_{\rm F}}{\sqrt{2}}\, j^\alpha\, j^+_\alpha \tag{22}$$

where

$$j^+_\alpha = 2\,[\bar n_L\gamma_\alpha p_L \;+\; \bar e_L\gamma_\alpha\nu_{eL} \;+\; \bar\mu_L\gamma_\alpha\nu_{\mu L}] \tag{23}$$

is the conjugated current.

In (21) the neutrino field that enters into the current together with the electron field (muon field) is denoted by ν_e (ν_μ). We will call the corresponding particles the electron neutrino and the muon neutrino. It was proved in the famous 1962 Brookhaven neutrino experiment that ν_e and ν_μ are different particles. We will discuss this experiment in the next section. Now we will continue the discussion of the current × current Hamiltonian. There are terms of two types in the Hamiltonian (22): nondiagonal and diagonal. Nondiagonal terms are given by

$$\begin{aligned}\mathcal{H}_I^{\rm nd} = \frac{G_{\rm F}}{\sqrt{2}}4\{&[(\bar p_L\gamma^\alpha n)(\bar e_L\gamma_\alpha\nu_{eL}) \;+\; h.c.] \;+\\ &+[(\bar p_L\gamma^\alpha n_L)(\bar\mu_L\gamma_\alpha\nu_{\mu L}) \;+\; h.c.] \;+\\ &\;+[(\bar e_L\gamma^\alpha\nu_{eL})(\bar\nu_{\mu L}\gamma_\alpha\mu_L) \;+\; h.c.]\}\end{aligned} \tag{24}$$

The first term of this expression is the Hamiltonian of β-decay of the neutron (3), of the process

$$\bar\nu_e + p \to e^+ + n \tag{25}$$

and other processes.

The second term of (24) is the Hamiltonian of μ-capture (17), of the process

$$\nu_\mu + n \to \mu^- + p \tag{26}$$

and other processes.

Finally the third term of (24) is the Hamiltonian of μ-decay

$$\mu^+ \to e^+ + \nu_e + \bar\nu_\mu \tag{27}$$

and other processes.

Some processes that are described by nondiagonal terms of the Hamiltonian were observed in an experiment at the time when the current × current theory was proposed. This theory also predicted new weak processes such as the process of elastic scattering of the electron antineutrino on the electron

$$\bar\nu_e + e \to \bar\nu_e + e \tag{28}$$

and others. The Hamiltonian of these new processes is given by the diagonal terms of (22):

$$\mathcal{H}^{\mathrm{d}} = \frac{G_{\mathrm{F}}}{\sqrt{2}} 4[(\bar{\nu}_{eL}\gamma^{\alpha}e_L)(\bar{e}_L\gamma_{\alpha}\nu_{eL}) \ + \dots] \tag{29}$$

The predicted cross section of the process (28) is very small and its measurement was a difficult problem. After many years of efforts F. Reines et al observed the process (28) with reactor antineutrinos.

The detailed investigation of this and another similar processes showed that, except diagonal terms, in the Hamiltonian of such processes there are additional neutral current (NC) terms. We will discuss NC later.

There were two alternatives for the weak interaction theory: the current $\times$ current theory we described and the theory with an intermediate vector charged $W^{\pm}$ - boson. We will discuss now this last theory. Let us assume that there exists heavy particles $W^{\pm}$ with spin equal to 1 and charges $\pm e$ and that the fundamental weak interaction has the form

$$\mathcal{H} = \frac{g}{2\sqrt{2}} j_{\alpha} W^{\alpha} \ + \ h.c. \tag{30}$$

where g is the interaction constant and the current j^{α} is given by the expression (21). It is possible to show that at energies much less than the mass of the W-boson m_W for the processes with a virtual (intermediate) W-boson the current $\times$ current theory and the theory with the W-boson are equivalent.

In fact, let us consider μ-decay

$$\mu^- \to e^- + \bar{\nu}_e + \nu_{\mu} \tag{31}$$

In quantum field theory the processes are described by Feynman diagrams that are the convenient language and computational tool of physicists. With the help of special rules Feynman diagrams allows one to calculate the probabilities of decay, cross sections and other measurable quantities.

In the current $\times$ current theory the decay (31) is the process of the first order in perturbation theory in the constant G_F and its Feynman diagram is presented in Fig. 5. In the theory with the W-boson the decay (31) is the process of second order in perturbation theory in the constant g. The Feynman diagram of the process is presented in Fig. 6. Fig. 6 describes the following chain of transitions: the initial μ^- emits the final ν_{μ} and a virtual W^-; the vector boson propagates in the virtual state; the virtual W^-- boson decays into the final e^- and $\bar{\nu}_e$. At every vertex the conservation of 4-momenta takes place. This ensures the conservation of energy and momentum for the whole process. For a free particle the square of the 4-momentum is equal to the square of its mass. This is not the case for a virtual particle. For the square of the 4-momentum of the W-boson we have $q^2 = (p - p')^2$ where p and p' are the 4-momenta of μ^- and ν_{μ}, respectively. If the mass squared of the W boson m_W^2 is much larger than q^2 then the propagator of the W-boson (dashed line in Fig. 6) gives to the matrix element of the process the contribution proportional

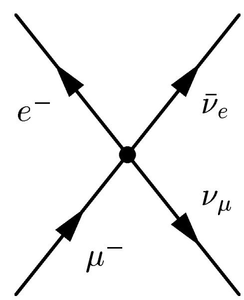


Figure 5: The Feynman diagram of the decay $\mu^- \to e^-\bar{\nu}_e\nu_\mu$ in the current $\times$ current theory.

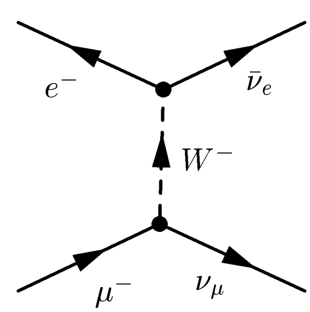


Figure 6: The Feynman diagram of the decay $\mu^- \to e^-\bar{\nu}_e\nu_\mu$ in the theory with intermediate W boson.

to $\frac{1}{m_W^2}$. The diagrams in Fig. 5 and Fig. 6 are equivalent if the Fermi constant is connected to the constant g by the relation

$$\frac{G_{\rm F}}{\sqrt{2}} = \frac{g^2}{8m_W^2} \tag{32}$$

The universal current $\times$ current theory of the weak interactions, as well the theory with the intermediate W-boson, allowed one to describe the data of many experiments. Nevertheless both theories could not be considered as a final theory of the weak interactions. The main reason was that both theories were not renormalizable quantum field theories. The probability of transitions calculated in lowest order perturbation theory were in a good agreement with experimental data. However, the corrections due to higher orders of perturbation theory cannot be calculated: they contained divergent integrals from which it could not be found the finite corrections by the renormalization of masses and interaction constants. At that time the only known renormalizable theory, that allowed to calculate the higher order corrections and that was in an excellent agreement with experiment, was quantum electrodynamics.

The enormous progress in the understanding of weak interactions is connected with the development of the Glashow-Weinberg-Salam renormalizable theory of weak and electromagnetic interactions, the, so called, Standard Model (SM). We will discuss this theory later.

7 Discovery of the ν_μ. Electron and muon lepton numbers

The mass of the muon is approximately 200 times larger than the electron mass (m_μ=105.66 MeV and m_e=0.51 MeV). From the very beginning of the investigation of muons the possible decay channel

$$\mu \to e + \gamma \tag{33}$$

was searched for. No indications in favor of this decay were found. In the first experiments that were done at the end of the forties, for the upper bound of the ratio R of the probability of the decay $\mu^+ \to e^+ + \gamma$ to the probability of the decay $\mu^+ \to e^+ + \nu_e + \bar\nu_\mu$, which is the main decay channel of muon, it was found that $R < 10^{-2}$. At present the upper bound of R is found to be $R < 1.2 \times 10^{-11}$

If the muon and electron neutrinos are the same particles the process (33) is possible. At the end of fifties the probability of the decay $\mu \to e + \gamma$ was calculated in a nonrenormalizable theory with W-boson and the estimated value of the ratio R was larger than existed at that time upper bound ($R < 10^{-8}$). This was a possible indication that ν_e and ν_μ were different particles. It was necessary, however, to check this in a direct experiment. Such an experiment was proposed by B. Pontecorvo in 1959 and it was done by L. Lederman, M. Schwarz, J. Steinberger et al in 1962 in Brookhaven (USA).

The Brookhaven experiment was the first experiment that has been done with neutrinos from an accelerator. The beam of pions in this experiment was produced by the bombardment of a Be target by 15 GeV protons. Neutrinos were produced in the decays of pions in a decay channel (about 20 m long). After the channel there was an iron shielding 13.5 m thick, in which charged particles were absorbed. After the shielding there was a neutrino detector (about 10 tons).

There are two decay modes of the π^+:

$$\pi^+ \to \mu^+ + \nu_\mu \tag{34}$$

$$\pi^+ \to e^+ + \nu_e \tag{35}$$

In the Feynman-Gell-Mann theory the decay (35) is strongly suppressed. In fact, let us consider this decay in the rest frame of the pion. In this frame the e^+ and the neutrino are moving in opposite directions. The helicity of the neutrino is equal to -1. If we neglect the mass of the positron the helicity of the positron will be equal to $+1$ (the helicity of the positron in this case will be the same as the helicity of the antineutrino) Thus, the projection of the total angular momentum on the direction of the momentum of the positron will be equal to 1. However, the spin of the pion is equal to zero and the projection of the initial angular momentum on any direction is equal to zero. Thus, in the limit $m_e \to 0$ the decay (35) is forbidden. For $m_e \neq 0$ the decay (35) is not forbidden but it is strongly suppressed with respect to the decay (34). The ratio of the probabilities of the decays (35) and (34) is given by

$$R = (\frac{m_e}{m_\mu})^2 \frac{(1 - \frac{m_e^2}{m_\pi^2})^2}{(1 - \frac{m_\mu^2}{m_\pi^2})^2} \simeq 1.2 \cdot 10^{-4} \tag{36}$$

Thus, in decays of pions predominantly muon neutrinos are produced.

In the neutrino detector the processes of the interaction of neutrinos with nucleons were observed. If ν_μ and ν_e are different particles, muons produced in the process

$$\nu_\mu + N \to \mu^- + X \tag{37}$$

will be observed in the detector (X mean any hadrons). If ν_μ and ν_e are the same particles, the process

$$\nu_\mu + N \to e^- + X \tag{38}$$

is also possible and in the detector muons *and electrons* will be observed. Due to $\mu - e$ universality of the weak interaction the cross sections of the processes (37) and (38) will be practically the same and equal numbers of muons and electrons will be observed in the detector.

In the Brookhaven experiment 29 muons were detected. Only 6 electron events were observed. All electron events could be explained as background

	$\nu_e,\ e^-$	$\nu_\mu,\ \mu^-$	hadrons, $\gamma, \ldots$
L_e	1	0	0
L_μ	0	1	0

Table 1: Lepton numbers of particles.

events. Thus, it was proved that the process (38) is forbidden, i.e. *muon and electron neutrinos are different particles.*

To explain the results of the Brookhaven and other experiments, it is necessary to introduce two conserved lepton numbers: the electron lepton number L_e and the muon lepton number L_μ. The electron and muon lepton numbers of different particles are given in the Table 1.

From the conservation of the total electron and total muon lepton numbers

$$\sum L_e = \text{const}\,, \qquad \sum L_\mu = \text{const}\,. \tag{39}$$

it follows that the decays

$$\mu^+ \to e^+\gamma\,, \qquad \mu^+ \to e^+e^-e^+ \tag{40}$$

and other similar processes are forbidden.

Let us notice that from the modern point of view the family lepton numbers L_μ and L_e are violated due to small neutrino masses and neutrino mixing. This violation can be revealed in neutrino oscillations that we will discuss later.

8 Strange particles in the current × current interaction. The Cabibbo angle

In the fifties a large family of new particles $K^\pm$, K^0, $\bar{K}^0$, Λ, $\Sigma^{\pm,0}$, $\Xi^{-,0}$ was discovered. These particles were called strange particles.

Strange particles are produced in nucleon-nucleon and pion-nucleon collisions only in pairs. For example, the process

$$\pi^- + p \to \Lambda + K^0 \tag{41}$$

in which two strange particles are produced, was observed . On the other hand, it was shown that the process of production of one strange particle

$$n + p \to \Lambda + p \tag{42}$$

was forbidden.

In order to explain the fact of the production of strange particles in pairs in nucleon-nucleon and pion-nucleon collisions it was necessary to introduce a conserved quantum number that distinguished strange particles from nonstrange ones (nucleons, pions and others). This quantum number was called *strangeness*

S . If we assume that the nucleon and pion have $S = 0$, K^0 has $S = 1$ and Λ has $S = -1$, then the process (41) is allowed and the process (42) is forbidden.

Strange particles are unstable and in their decay the strangeness is not conserved. The investigation of processes such as

$$\begin{aligned} K^+ \to \mu^+ + \nu_\mu, \quad & \Lambda \to n + e^- + \bar{\nu}_e \ , \\ \Sigma^- \to n + e^- + \bar{\nu}_e \quad & \Xi^- \to \Lambda + e^- + \bar{\nu}_e \end{aligned} \tag{43}$$

and others allowed to formulate two phenomenological rules that govern these decays.

I. In decays of strange particles the strangeness is changed by one, i.e., $|\Delta S| = 1$.

II. The rule $\Delta Q = \Delta S$ is satisfied ($\Delta Q = Q_f - Q_i$ and $\Delta S = S_f - S_i$, $Q_i(S_i)$ and $Q_f(S_f)$ are initial (final) total charge and strangeness of hadrons).

According to rule I the decay

$$\Xi^- \to \Lambda + e^- + \bar{\nu}_e \tag{44}$$

is allowed and the decay

$$\Xi^- \to n + e^- + \bar{\nu}_e \tag{45}$$

is forbidden (the strangeness of Ξ is equal to -2).

According to rule II the decay

$$\Sigma^+ \to n + e^+ + \bar{\nu}_e \tag{46}$$

is forbidden (the strangeness of $\Sigma^{\pm}$ is equal to -1). All these predictions are in perfect agreement with experiments.

In 1964 Gell-Mann and Zweig made the crucial assumption that the proton, the neutron, the pions, the strange particles and all other hadrons are bound states of *quarks*. Quarks are particles with spin 1/2, electric charges 2/3 or -1/3 (in the units of the electric charge of the proton) and baryon number equal to 1/3. Gell-Mann and Zweig introduced three quarks, constituents of nonstrange and strange hadrons: nonstrange quarks u and d with charges 2/3 and -1/3, respectively and a strange quark s with charge -1/3 and strangeness -1. In the framework of the quark model the proton is a bound state of two u-quarks and a d-quark, the π^+ -meson is a bound state of a u-quark and a $\bar{d}$-antiquark, the K^+-meson is a bound state of a u-quark and a $\bar{s}$-antiquark, the Λ- hyperon is a bound state of a u-quark, a d-quark and a s-quark etc. The correctness of the quark hypothesis was confirmed by numerous experiments. Later we will discuss the role of the neutrinos in revealing the quark structure of the nucleon.

If nucleons, pions, strange particles and other hadrons are not elementary particles and instead are bound states of quarks it is natural to assume that the fundamental weak interaction is the interaction of leptons, neutrinos *and quarks*. In this case the Feynman diagram of the β-decay of the neutron has the form presented in Fig. 7. Strange particles were included into the current

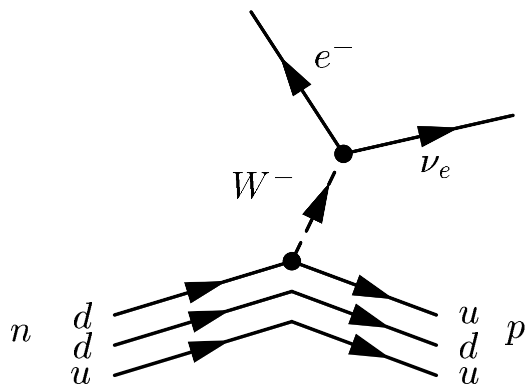


Figure 7: The Feynman diagram of the process $n \to pe^-\bar{\nu}_e$ in the quark model.

× current interaction by N. Cabibbo in 1963. The current $\bar{p}_L\gamma_\alpha n_L$ does not change strangeness and changes charge by one. The quark current that has such properties is $\bar{u}_L\gamma_\alpha d_L$. The quark current that changes charge by one and changes strangeness is $\bar{u}_L\gamma_\alpha s_L$ This current satisfies rules I and II *automatically.*

It was also known from the analysis of experimental data that decays of strange particles are suppressed with respect to the decays of nonstrange particles. To take into account this suppression N. Cabibbo introduced an additional parameter. This parameter is called the Cabibbo angle θ_C. For the quark weak current he proposed the following expression

$$j_\alpha^{\mathrm{C}} = 2[\cos\theta_C \bar{u}_L\gamma_\alpha d_L + \sin\theta_C \bar{u}_L\gamma_\alpha s_L] \tag{47}$$

It was shown that the weak interaction Hamiltonian with such a current allows one to describe experimental data. From the analysis of the data it was found that $\sin\theta_C \simeq 0.2$.

Let us write down the total weak current in the form

$$j_\alpha = 2[\bar{\nu}_{eL}\gamma_\alpha e_L + \bar{\nu}_{\mu L}\gamma_\alpha \mu_L + \bar{u}_L\gamma_\alpha d'_L] \tag{48}$$

where

$$d'_L = \cos\theta_C d_L + \sin\theta_C s_L \tag{49}$$

is the mixture of the fields of the d and s quarks.

Notice that there are two lepton terms and one quark term in the expression (48). In 1970 it was shown by Glashow, Illiopulos and Maiani that in the case of the current (48) the probability of the decays of the type

$$K^+ \to \pi^+ + \nu + \bar{\nu} \tag{50}$$

in which $\Delta S = -1$ and $\Delta Q = 0$ is significantly larger than the upper bound obtained in experiments. In order to avoid this problem Glashow, Illiopulos and

Maiani assumed that there exists a fourth quark with charge 2/3 and that there is an additional term in the weak current in which the field of the new quark enters. This new quark was called the charm quark (c). The weak currents took the form

$$j_\alpha = 2[\bar{\nu}_{eL}\gamma_\alpha e_L + \bar{\nu}_{\mu L}\gamma_\alpha \mu_L + \bar{u}_L\gamma_\alpha d'_L + \bar{c}_L\gamma_\alpha s'_L] \tag{51}$$

where

$$\begin{aligned} d'_L &= \cos\theta_C d_L + \sin\theta_C s_L \\ s'_L &= -\sin\theta_C d_L + \cos\theta_C s_L \end{aligned} \tag{52}$$

The symmetry between leptons and quarks was restored.

In 1976 the first charmed mesons $D^{\pm,0}$, bound states of charmed and u (d) quarks, were discovered in the experiments at $e^+ - e^-$ colliders. Later other charmed mesons and charmed baryons were also observed.

9 Glashow-Weinberg-Salam theory of the electroweak interaction

The current $\times$ current theory of the weak interaction and the theory with heavy charged vector $W^\pm$ bosons to lowest order perturbation theory allowed one to describe all existing experimental data. However, both theories were only effective nonrenormalizable theories: in the framework of these theories it was not possible to calculate corrections due to higher orders of perturbation theory.

The modern renormalizable theory of the weak interaction (S.L. Glashow (1961), S. Weinberg (1967) and A. Salam (1968)) appeared as a result of *unification of the weak and electromagnetic interactions into an electroweak interaction* .This theory which is called the Standard Model (SM) is one of the greatest achievements of particle physics in the 20th century. This theory successfully predicted the existence of families of new hadrons (charmed, bottom and top), new interactions (Neutral Currents), the existence of $W^\pm$ and Z^0 bosons, masses of these particles etc. All predictions of the Standard Model are in perfect agreement with existing experimental data including very precise high-energy data that were obtained in experiments at $e^+ - e^-$ colliders at CERN (Geneva) and SLAC (Stanford).

The Hamiltonian of the electromagnetic interaction has the form of the scalar product of the electromagnetic current and the electromagnetic field

$$\mathcal{H}_I^{\rm em} = e\ j_\alpha^{\rm em}\ A^\alpha \tag{53}$$

Here

$$j_\alpha^{\rm em} = \sum_{l=e,\mu} (-1)\bar{l}\gamma_\alpha l + \sum_{q=u,d,\dots} e_q \bar{q}\gamma_\alpha q \tag{54}$$

is the electromagnetic current of leptons and quarks ($e_u = 2/3$, $e_d = -1/3, \dots$)

The electromagnetic field A_α is determined up to the derivative of an arbitrary function. The observable physical quantities are not changed if we make the following transformation

$$A_\alpha(x) \to A_\alpha(x) - \frac{1}{e}\frac{\partial \Lambda(x)}{\partial x^\alpha} \tag{55}$$

and change correspondingly the unobserved phases of the quark and lepton fields. In (55) $\Lambda(x)$ is an arbitrary function. This invariance is called gauge invariance and the electromagnetic field is an example of a gauge field. A gauge field is a vector field and corresponding particles, quanta of the gauge field, have spin equal to one.

Weak and electromagnetic interactions are unified on the basis of the generalized Yang-Mills gauge invariance. The corresponding gauge fields include not only the electromagnetic field but also fields of the charged vector particles.

The SM is based on spontaneously broken SU(2) $\times$ U(1) gauge symmetry which assumes the existence, in addition to the massless photon, three massive spin 1 particles: two charged and one neutral. The Hamiltonian of the SM has the following form

$$\mathcal{H}_I = (\frac{g}{2\sqrt{2}} j_\alpha W^\alpha + h.c.) + \frac{g}{2\cos\theta_W} j^0_\alpha Z^\alpha + e j^{\text{em}}_\alpha A^\alpha \tag{56}$$

Here

$$j^0_\alpha = 2 j^3_\alpha - 2\sin^2\theta_W j^{\text{em}}_\alpha = \sum_l \bar{\nu}_{lL}\gamma_\alpha \nu_{lL} + \dots \tag{57}$$

is the so called neutral current and θ_W is a parameter (Weinberg or weak angle).

The first term of (56) is the charged current (CC) interaction, that we have discussed before. The second term is a new neutral current (NC) interaction. Third term is the well known electromagnetic interaction.

Thus, the unified theory of the electroweak interaction *predicted the existence of a new neutral vector boson Z^0 and a new NC interaction.*

This new interaction means the existence of new weak interaction processes. The first processes were discovered in 1973 at CERN. We will discuss this discovery in the next chapter. Charged $W^\pm$ and neutral Z^0 bosons were discovered in experiments at the proton-antiproton collider at CERN in 1983.

10 The discovery of neutral currents

Beams of neutrinos (antineutrinos) that can be obtained at accelerators are mainly the beams of muon neutrinos (antineutrinos) from decays of pions with a small (a few %) admixture of electron neutrinos and antineutrinos from the decays of kaons and muons.

We will discuss NC processes that were observed in experiments with the beam of high energy neutrinos at CERN in the beginning of the eighties.

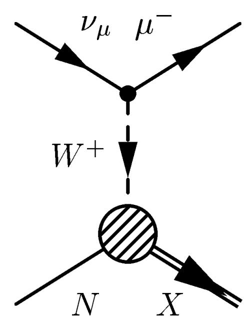


Figure 8: The Feynman diagram of the inclusive process $\nu_\mu + N \to \mu^- + X$.

If the muon neutrino (antineutrino) interacts with a nucleon the following processes

$$\nu_\mu(\bar{\nu}_\mu) + N \to \mu^-(\mu^+) + X \tag{58}$$

are possible. The diagram of the neutrino process is presented in Fig. 8. This Feynman diagram describes the following steps: due to the CC interaction (56) the initial ν_μ produces the final μ^- and virtual W^+ boson; the virtual W^+ boson propagates and is absorbed by a quark inside of the nucleon. As a result the initial quark is transferred into the final quark (the initial nucleon is transferred into final hadron states). If only the final muon is observed and the effective mass of the final hadrons is much larger than the mass of the nucleon, the process is called an inclusive deep inelastic process.

The process (58) is a typical weak interaction process: absorption of a neutrino is *accompanied* by the production of a corresponding charged lepton (like in β-decay of the neutron, the production of an electron is accompanied by emission of a $\bar{\nu}_e$).

If there is the NC interaction (56) the deep inelastic NC processes

$$\nu_\mu(\bar{\nu}_\mu) + N \to \nu_\mu(\bar{\nu}_\mu) + X \tag{59}$$

with a neutrino (and not a muon) in the final state become possible (see diagram Fig. 9). In the Feynman diagram Fig. 9 due to the NC interaction (56) the initial ν_μ produces the final ν_μ and a virtual Z^0 boson. The virtual Z^0 boson propagates and is absorbed by a quark inside the nucleon. As a result of this absorption the initial nucleon is transferred in a final hadron state.

Such a new weak process was first observed at CERN in 1973 in the bubble chamber "Gargamelle". It was found that the ratio of the NC and CC cross sections is approximately equal to 0.3. Thus, investigation of neutrino processes allowed one to *discover new weak processes.* The discovery of NC processes and

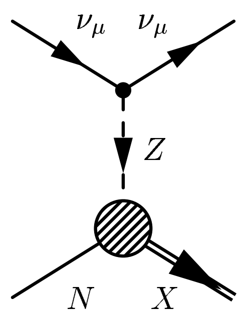


Figure 9: The Feynman diagram of the inclusive process $\nu_\mu + N \to \nu_\mu + X$.

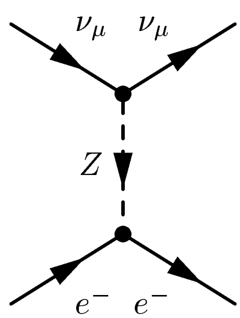


Figure 10: The Feynman diagram of the process $\nu_\mu + e \to \nu_\mu + e$.

their detailed investigation were crucial confirmation of the Glashow-Weinberg-Salam unified theory of the weak and electromagnetic interactions.

Another NC process is the process of elastic scattering of ν_μ ($\bar\nu_\mu$) on electrons (see diagram Fig. 10)

$$\nu_\mu(\bar\nu_\mu) + e \to \nu_\mu(\bar\nu_\mu) + e \tag{60}$$

The cross sections of these processes were measured at high energies by the CHARM collaboration at CERN. For the cross sections it was found

$$\sigma_{\nu_\mu e} = (1.9 \pm 0.4 \pm 0.4)10^{-42}\ \frac{E}{\mathrm{GeV}}\ cm^2 \tag{61}$$

$$\sigma_{\bar\nu_\mu e} = (1.5 \pm 0.3 \pm 0.4)10^{-42}\ \frac{E}{\mathrm{GeV}}\ cm^2 \tag{62}$$

From these measured cross sections the following value of the parameter $\sin^2\theta_W$ was found

$$\sin^2\theta_W = 0.215 \pm 0.032 \pm 0.012. \tag{63}$$

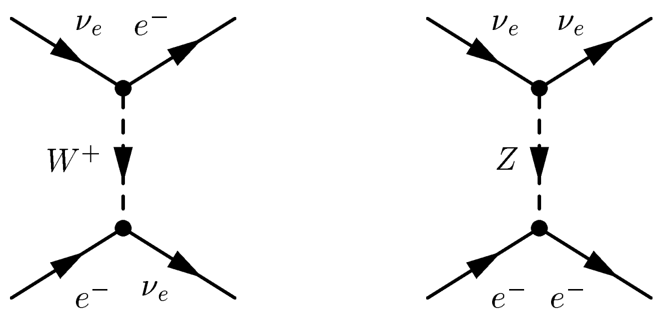


Figure 11: The Feynman diagrams of the process $\nu_e + e \to \nu_e + e$.

This value of the parameter $\sin^2\theta_W$ is in agreement with the values obtained from the measurements of all other NC processes.

Only the NC interaction gives contribution to the cross sections of the processes (60). The processes of elastic scattering of the ν_e and $\bar{\nu}_e$ on electrons

$$\nu_e(\bar{\nu}_e) + e \to \nu_e(\bar{\nu}_e) + e \tag{64}$$

are due to W and Z exchanges (see diagram Fig. 11). Cross sections of these processes were measured in the experiments at the reactors and at the Los Alamos Meson Factory. Notice that, the CC part of the amplitude of the elastic scattering of ν_e on the electron (diagram Fig. 11) plays a crucial role in the propagation of neutrinos through matter (see below)

Effects of neutral currents were also measured in the inclusive deep inelastic scattering of longitudinally polarized electrons and muons on nucleons (SLAC and CERN) and in atomic transitions. All NC data perfectly confirm the Standard Model of electroweak interactions. For the parameter $\sin^2\theta_W$, it was found the value

$$\sin^2\theta_W = 0.23155 \pm 0.00019. \tag{65}$$

11 Deep inelastic neutrino-nucleon scattering and quark structure of the nucleon

Experiments on the investigation of the deep inelastic CC neutrino processes

$$\nu_\mu + N \quad \to \quad \mu^- + X \tag{66}$$
$$\bar{\nu}_\mu + N \quad \to \quad \mu^+ + X \tag{67}$$

that have been done at Fermilab (USA) and CERN in the seventies and eighties were very important for establishing the quark structure of the nucleon. In particle physics these experiments and also the experiments on the deep inelastic scattering of electrons (muons) on nuclei played the role of the famous Rutherford experiments in atomic physics. Like the Rutherford experiments which allowed one to establish the existence of heavy nuclei in atoms, these experiments allowed one to establish the existence of quarks and antiquarks in nucleons.

Let us first introduce the variables that are usually used to describe deep inelastic scattering

$$x = \frac{Q^2}{2pq}, \quad y = \frac{pq}{pk}, \quad E = \frac{pk}{M} \tag{68}$$

where $q = k - k'$ is the 4-momentum transfer (4-momentum of the W-boson), $Q^2 = -q^2$ and M is the mass of the nucleon. (p, k and k' are 4-momenta of the initial nucleon, neutrino and final muon, respectively).

From conservation of energy and momentum it follows that the variable x takes values in the interval $0 \leq x \leq 1$. In the lab. system (the system where the initial nucleon is at rest) the variable y becomes

$$y = \frac{E - E'}{E} \tag{69}$$

where E and E' are the energies of the initial neutrino and final muon, respectively. Thus, y is the relative energy that is transfered to the hadrons. At high energies $0 \leq y \leq 1$. Let us also introduce the variable $\nu = pq/M$. In the region of deep inelastic scattering $\nu \gg M$ and $Q^2 \gg M^2$.

Let us consider the processes of interaction of the neutrino with the u and d quarks and antiquarks

$$\nu_\mu \quad + \quad d \to \mu^- + u \tag{70}$$

$$\nu_\mu \quad + \quad \bar{u} \to \mu^- + \bar{d}. \tag{71}$$

In the deep inelastic region we can neglect the masses of the quarks and from conservation of energy and momentum it follows that the virtual W-boson interacts only with those quarks, which have momentum xp, where p is the nucleon momentum. The contributions to the differential cross section of the process $\nu_\mu + p \to \mu^- + X$ of the subprocesses (70) and (71) are given by the following expression

$$\frac{d^2\sigma_{\nu p}}{dxdy} = 2\sigma_0 x[d(x) + (1-y)^2 \bar{u}(x)]. \tag{72}$$

Here

$$\sigma_0 = \frac{G_F^2}{\pi} ME \simeq 1.5 \cdot 10^{-38} \frac{E}{\text{GeV}} \text{ cm}^2 \tag{73}$$

is the total cross section of the interaction of the neutrino with a point-like particle with mass M, $d(x)$ and $\bar{u}(x)$ are number-densities of the d-quarks and $\bar{u}$-antiquarks with momentum xp in the proton.

The dependence of the cross sections on the variable y is determined by the helicities of the initial particles. Let us consider the process (71) in the center of mass system. In this system the total momentum of the initial (final) particles is equal to zero . The helicity of the neutrino is equal to -1 and the helicity of the antiquark $\bar{u}$ is equal to 1 (we neglect quark masses). Thus, the projection of the total angular momentum on the direction of the momentum of the neutrino is equal to $2 \times (-1/2) = -1$. Let us consider the emission of a μ^- in the backward direction. This case corresponds to $y = 1$ (the energy, that is transferred to the hadrons, is maximal). The helicity of the μ^- is equal to -1 and the projection of the total angular momentum on the direction of the momentum of the neutrino is equal to $+1$ in this case. Thus, the emission of the μ^- in the backward direction is forbidden by conservation of total angular momentum. This corresponds to the $(1-y)^2$ dependence of the contribution of the antiquarks to the cross section of the process (66).

In the case of the process (70) the projections of the total angular momentum on the direction of the momentum of the neutrinos are equal to zero for the initial and final particles. Thus, emission of μ^- in backward direction is allowed. This corresponds to the absence of an y-dependence in the contribution of quarks to the cross section (73).

In neutrino experiments the target nuclei are usually nuclei with approximately equal numbers of protons and neutrons. If we take into account the contribution of only u and d quarks, for the cross sections, averaged over p and n, we obtain the following expression

$$\frac{d^2\sigma_{\nu N}}{dxdy} = \sigma_0 x[q(x) + (1-y)^2 q(x)]. \tag{74}$$

Here

$$\begin{aligned} q(x) &= u(x) + d(x) \\ \bar{q}(x) &= \bar{u}(x) + \bar{d}(x) \end{aligned} \tag{75}$$

Here $u(x)$ is the density of u-quarks in the proton (d-quarks in the neutron) and so on.

For the averaged cross section of the process

$$\bar{\nu}_\mu + N \to \mu^+ + X \tag{76}$$

we have

$$\frac{d^2\sigma_{\bar{\nu}}}{dxdy} = \sigma_0 x[(1-y)^2 q(x) + \bar{q}(x)] \tag{77}$$

The expressions (73), (74) and (77) were obtained in the so- called naive quark-parton model in which interactions between quarks are neglected. If we take into account the interaction of quarks with gluons in this case the expressions for the cross sections have the same form, but the quark and antiquark distribution functions q and $\bar{q}$ will depend not only on the variable x but also on $\ln Q^2$.

Expressions (74) and (77) allows one to describe existing experimental data. From these expressions it is possible to obtain information on the distribution of quarks and antiquarks in the nucleon.

For y - distributions from (74) and (77) we have

$$\begin{aligned} \frac{d\sigma_{\nu N}}{dy} &= \sigma_0[Q + (1-y)^2\bar{Q}] \\ \frac{d\sigma_{\bar{\nu} N}}{dy} &= \sigma_0[(1-y)^2 Q + \bar{Q}] \end{aligned} \tag{78}$$

where

$$Q = \int_0^1 xq(x)dx, \qquad \bar{Q} = \int_0^1 x\bar{q}(x)dx \tag{79}$$

are the fractions of the momentum of the nucleon carried by quarks and antiquarks, respectively (in the system $q^0 = 0$, in which the momentum of the nucleon is much larger than its mass)

From the relations (78) it follows that at $y = 0$ the cross sections of the processes (66) and (67) must be equal. This is confirmed by the data of the neutrino experiments. From the data of the CDHS experiment at CERN with neutrino energies in the range $30 < E < 200$GeV it was found that

$$\left(\frac{d\sigma_{\bar{\nu} N}}{dy}\right)_{y=0} \Bigg/ \left(\frac{d\sigma_{\nu N}}{dy}\right)_{y=p} = 1.01 \pm 0.07. \tag{80}$$

If the contribution of antiquarks into the cross sections are much less than the contribution of quarks, we must expect weak dependence of the cross section $\frac{d\sigma_{\nu N}}{dy}$ on the y and $(1-y)^2$-dependence of the cross section $\frac{d\sigma_{\bar{\nu} N}}{dy}$. This behavior was observed in experiments. From the analysis of the CDHS data it follows

$$\frac{\bar{Q}}{Q + \bar{Q}} = 0.15 \pm 0.01 \tag{81}$$

Thus, the contribution of antiquarks to the nucleon momentum is about 15 % of total contribution of the quarks and antiquarks.

For the fraction of the nucleon momentum that is carried by quarks and antiquarks it was found that

$$Q + \bar{Q} = 0.492 \pm 0.006 \pm 0.019 \tag{82}$$

Thus, neutrino experiments proved that not all the nucleon momentum is carried by the quarks and antiquarks. The other part of the nucleon momentum is carried by the gluons, vector particles that interact with quarks.

Finally, from the quark-parton model it follows that the total neutrino and antineutrino cross sections depend linearly on neutrino energy E.

$$\begin{aligned}
\sigma_{\nu N} &= \frac{G^2}{\pi} M(Q + \frac{1}{3}\bar{Q})E \\
\sigma_{\bar{\nu} N} &= \frac{G^2}{\pi} M(\frac{1}{3}Q + \bar{Q})E
\end{aligned} \tag{83}$$

The data of the experiments perfectly confirm this prediction of the theory:

$$\begin{aligned}
\sigma_{\nu N} &= (0.686 \pm 0.019) \times 10^{-38} \frac{E}{\mathrm{GeV}} \mathrm{cm}^2 \\
\sigma_{\bar{\nu} N} &= (0.339 \pm 0.010) \times 10^{-38} \frac{E}{\mathrm{GeV}} \mathrm{cm}^2
\end{aligned} \tag{84}$$

Thus, the investigation of the high energy neutrino processes allowed one to establish the quark structure of the nucleon and to obtain important information on the distribution functions of quarks and antiquarks in the nucleon.

12 Neutrino masses. Introduction

From all existing data it follows that the interaction of neutrinos with matter is given by the Standard Model, However, neutrino masses, neutrino magnetic moments and other fundamental neutrino properties are basically unknown. We now come to the problem of *the neutrino masses and neutrino mixing.*

The brief history of neutrino masses is the following. Pauli introduced the neutrino as a particle with a mass (as a constituent of nuclei). He thought that the mass of the neutrino is less than the electron mass. Fermi and Perrin proposed the first method of measuring the neutrino mass based on the measurement of the shape of the high energy part of the β-decay spectrum. This part of the spectrum is due to the emission of a neutrino with small energy and effects of the neutrino mass in that part of the spectrum is the most pronounced. In experiments on the determination of the neutrino mass by the this method, the decay of tritium

$$^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_e \tag{85}$$

is usually investigated.

In the first experiments that were done in the forties no effects of a neutrino mass were seen. From these experiments it was found that the upper bound of the neutrino mass is much less than the electron mass:

$$m_\nu < 500 \text{ eV}. \tag{86}$$

With the improvement of experimental technique this upper bound became much smaller and at the time, when the parity violation in β-decay was discovered, the upper bound of the neutrino mass was about 100 eV.

The theory of the two-component neutrino (Landau, Lee and Young and Salam) was based on the *assumption* that the neutrino mass is equal to zero. After the success of this theory during many years there was a general belief that all neutrinos are massless particles. The Glashow-Weinberg-Salam theory was also based on this assumption.

In 1957-58 B. Pontecorvo considered the possibility of *a small but nonzero neutrino masses*. The only known massless particle is the photon. There is a symmetry reason for the photon to be massless-the gauge invariance of quantum electrodynamics. B. Pontecorvo put attention that there is no such a principle in the case of the neutrino. He showed that, if states of neutrinos produced in weak decays are superpositions of the states of neutrinos with small masses, *neutrino oscillations* will take place in the beams of the neutrinos in vacuum, similar to well known $K^0 \to \bar{K}^0$ oscillations. B. Pontecorvo showed that the search for neutrino oscillations is a very sensitive method of the measurement of small neutrino masses.

In 1962 at the time of the Brookhaven experiment Maki, Nakagawa and Sakata proposed some model in which the nucleon was considered as a bound state of some vector particle and massive neutrinos. They assumed that the fields of ν_e and ν_μ are linear orthogonal combinations of the fields of the massive neutrinos and pointed out that in such a case transition of muon neutrinos into electron neutrinos becomes possible.

In the seventies in Dubna (Russia) and other places in the framework of the SM the neutrino masses and mixing were considered as a phenomena analogous to the Cabibbo-GIM quark mixing. The neutrino oscillations between two types of neutrinos were discussed and the different experiments on the search for neutrino oscillations were proposed.

At that time the majority of physicists still believed that neutrinos are massless particles. The opinion about the neutrino masses drastically changed in the end of the seventies with the appearance of models beyond the Standard Model such as models of Grand Unification. These models are based on large symmetry groups and fields of neutrinos enter into the same multiplets of the groups as the fields of leptons and quarks. A mechanism of the generation of the masses of quarks and leptons generally provides also masses to the neutrinos. The neutrino masses and mixing started to be considered as phenomena connected with physics beyond the Standard Model.

In the eighties special experiments on the search for neutrino oscillation started. The problem of the neutrino masses and neutrino oscillations became the most challenging and important problems of neutrino physics.

13 Discovery of the τ-lepton, b and t-quarks. The number of flavor neutrinos

Up to now we have considered four leptons: the two charged leptons e and μ and the two neutrinos ν_e and ν_μ. In 1975 the third heavy charged lepton τ with a mass of about 1.8 GeV was discovered by M. Perl et al. at the $e^+ - e^-$ collider at Stanford (USA).

In the framework of the SM this was a discovery of the third family of leptons and quarks. It meant that a new type of neutrino ν_τ and two new quarks with charges 2/3 and $-1/3$ must exist. These quarks were called the top and bottom. The real triumph of the Standard model was the discovery of the bottom particles in the eighties and top quark in the nineties.

After these discoveries the charged current of leptons and quarks took the form

$$j_\alpha^{CC} = 2(\sum_{l=e,\mu,\tau} \bar\nu_{lL}\gamma_\alpha l_L + \overline{u}_L\gamma_\alpha d'_L + \overline{c}_L\gamma_\alpha s'_L + \overline{t}_L\gamma_\alpha b'_L) \tag{87}$$

where

$$d'_L = \sum_{q=d,s,b} V_{uq} q_L, \qquad s'_L = \sum_{q=d,s,b} V_{cq} q_L, \qquad b'_L = \sum_{q=d,s,b} V_{tq} q_L \tag{88}$$

Here V is the unitary matrix that is called the Cabibbo-Kobayashi-Maskawa matrix. The elements of this matrix are well- known from the data of numerous experiments.

How many families of quarks and leptons exist in Nature? The investigation of neutrino processes allowed to answer this fundamental question. As we have seen, the number of families is equal to the number of neutrino types (neutrino flavors). This number was measured in experiments at the $e^+ - e^-$ colliders at SLC (Stanford) and LEP (CERN). From the data of these experiments the probability (width) of the decay

$$Z \to \nu_l + \bar\nu_l \qquad l = e, \mu, \tau, \dots \tag{89}$$

was determined. The width of the decay (89) is proportional to the number of neutrino flavors n_ν. From the data of the recent LEP experiments it was found that

$$n_\nu = 2.994 \pm 0.012. \tag{90}$$

Thus, only three flavor neutrinos ν_e, ν_μ, ν_τ and, consequently, three families of quarks and leptons exist in Nature.

14 Neutrino mixing

If the neutrinos are massless, the Standard weak interaction conserve three lepton numbers L_e, L_μ and L_τ:

$$\sum L_e = const, \quad \sum L_\mu = const, \quad \sum L_\tau = const \tag{91}$$

The values of the lepton numbers of the charged leptons and the neutrinos are given in Table 2.

	$\nu_e,\ e^-$	$\nu_\mu,\ \mu^-$	$\nu_\tau,\ \tau^-$	hadrons, $\gamma, \dots$
L_e	1	0	0	0
L_μ	0	1	0	0
L_τ	0	0	1	0

Table 2: Lepton numbers of neutrinos and charged leptons.

We will now assume that the neutrinos are massive and the lepton numbers are violated by *a neutrino mass term*. In this case fields of neutrinos ν_{eL}, $\nu_{\mu L}$ and $\nu_{\tau L}$ in the Lagrangian of the weak interaction will be linear combinations of the fields of neutrinos with definite masses

$$\nu_{lL} = \sum_{i=1,2,3} U_{li}\, \nu_{iL} \qquad (l = e, \mu, \tau) \tag{92}$$

Here U is unitary matrix ($UU^{+} = 1$) and ν_i are the fields of neutrinos with masses m_i.

Before we will come to the discussion of the consequences of neutrino mixing (92) let us notice that there are two types of particles with spin 1/2: Dirac particles and Majorana particles.

Dirac particles possess some conserved charges. Every Dirac particle has an antiparticle, the particle with the same mass and spin but opposite charge. The electron and the proton are examples of Dirac particles. Corresponding antiparticles are the positron and the antiproton.

Other possible particles with spin 1/2 are *Majorana particles* . All charges of the Majorana particles are equal to zero. Thus, a Majorana particle and a Majorana antiparticle are identical. Up to now Majorana particles were not observed. The massive neutrinos and neutralinos, particles predicted by models of supersymmetry, are possible candidates. Neutral bosons such as the photon, π^0 and other are well known neutral particles with integral spin that are identical to their antiparticles.

There are two possibilities of the violation of the lepton number conservation low:

I. The lepton numbers L_e, L_μ and L_τ are violated separately but the total lepton number $L = L_e + L_\mu + L_\tau$ is conserved

$$\sum L = const \tag{93}$$

In this case the neutrinos ν_i are Dirac particles that possess lepton number $L = 1$. The lepton number of the antineutrinos $\bar{\nu}_i$ is equal to -1. The Dirac neutrino masses and neutrino mixing can be generated in the framework of the SM by the same mechanism that is responsible for the generation of the masses and mixing of quarks.

II. There are no conserved lepton numbers.

In this case the massive neutrinos ν_i are Majorana particles. The Majorana neutrino masses and mixing can be generated only in the framework of the models beyond the SM.

If massive neutrinos are Majorana particles there exist a plausible mechanism of the generation of neutrino masses that connect the smallness of neutrino masses with the violation of lepton numbers at a mass scale M that is much larger than the masses of leptons and quarks. This is the so-called see-saw mechanism. The masses of neutrinos are given in the see-saw case by the relation

$$m_i \simeq \frac{(m_{\rm f}^i)^2}{M} \ll m_{\rm f}^i \qquad (i=1,2,3)\,. \tag{94}$$

where $m_{\rm f}^i$ is the mass of the lepton or quark in the ith family ($i=1,2,3$). Let us notice that in the see-saw case the neutrino masses satisfy the hierarchy relation

$$m_1 \ll m_2 \ll m_3 \tag{95}$$

that follows from the hierarchy of masses of the leptons (quarks) of the different families.

15 Neutrino oscillations

If there is the neutrino mixing

$$\nu_{lL} = \sum_{i=1}^{3} U_{li}\, \nu_{iL} \tag{96}$$

where ν_i is the field of a neutrino (Dirac or Majorana) with mass m_i, for the state vector of flavor neutrinos ν_e, ν_μ and ν_τ (neutrinos that are produced in weak decays and take part in CC or NC neutrino reactions) with momentum $\vec{p}$ we have

$$|\nu_l\rangle = \sum_{i=1}^{3} U_{li}^{*}\, |i\rangle\,. \tag{97}$$

where $|i\rangle$ is the state vector of neutrino with mass m_i and energy $E_i = \sqrt{m_i^2 + \vec{p}^2} \simeq p + \frac{m_i^2}{2p}, (m_i^2 \ll p^2)$. Thus, in the case of neutrino mixing the state of flavor neutrino is *a superposition of the states of neutrinos with different masses.*

The relation (97) is based on the assumption that the mass differences of neutrinos are so small that they cannot be revealed in the experiments on the investigation of processes of neutrino production and detection. The neutrino mass differences can be revealed in the neutrino oscillation experiments, special experiments with a large *macroscopic distance* between the neutrino source and the neutrino detector.

Let us assume that at $t=0$ the neutrino ν_l was produced ($l = e, \mu, \tau$). At time t we have for neutrino state

$$|\nu_l\rangle_t = \sum_{i=1}^{3} U_{li}^*\, e^{-iE_i t}\, |i\rangle\,. \tag{98}$$

The state $|\nu_l\rangle_t$ is the superposition of the states of *all* neutrinos ν_e, ν_μ and ν_τ

$$|\nu_l\rangle_t = \sum_{l'=e,\mu,\tau} |\nu_{l'}\rangle \mathcal{A}(\nu_l \to \nu_{l'})\,, \tag{99}$$

where

$$\mathcal{A}(\nu_l \to \nu_{l'}) = \sum_{i=1}^{3} U_{l'i} e^{-iE_i t} U_{li}^* \tag{100}$$

is the amplitude of the transition $\nu_l \to \nu_{l'}$ for time t. For the transition probability we have

$$P_{\nu_l \to \nu_{l'}} = \left|\delta_{l'l} + \sum_i U_{l'i}\, \left(e^{-i\,\Delta m_{i1}^2\,\frac{L}{2p}} - 1\right)\, U_{li}^*\right|^2\,. \tag{101}$$

Here $L \simeq t$ is the distance between the neutrino source and detector, and $\Delta m_{i1}^2 = m_i^2 - m_1^2$ (we have assumed that $m_1 < m_2 < m_3$).

Thus, the transition probabilities depend on the ratio L/p. If for all neutrino mass squared differences

$$\Delta m_{i1}^2\, \frac{L}{2p} \ll 1, \tag{102}$$

in this case $P(\nu_l \to \nu_{l'}) = \delta_{l'l}$ (no transitions between different flavor neutrinos).

In the simplest case of transitions between two types of neutrinos the mixing matrix has the form

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \tag{103}$$

where θ is the mixing angle (if $\theta = 0$ there is no mixing). For the transition probability we have in this case

$$\mathrm{P}(\nu_l \to \nu_{l'}) = \mathrm{P}(\nu_{l'} \to \nu_l) = \frac{1}{2}\sin^2 2\theta(1 - \cos\frac{\Delta m^2 L}{2p}) \tag{104}$$

where $l' \neq l$ and l, l' take the values (μ, τ) or (μ, e) or $(\,e, \tau)$ and $\Delta m^2 = m_2^2 - m_1^2$. For the survival probability we have

$$\mathrm{P}(\nu_l \to \nu_l) = \mathrm{P}(\nu_{l'} \to \nu_{l'}) = 1 - \frac{1}{2}\sin^2 2\theta(1 - \cos\frac{\Delta m^2 L}{2p}) \tag{105}$$

The expression (104) and (105) can be rewritten in the form

$$\mathrm{P}(\nu_l \to \nu_{l'}) = \frac{1}{2}\sin^2 2\theta \left(1 - \cos 2.53\Delta m^2 \frac{L}{E}\right) \tag{106}$$

$$\mathrm{P}(\nu_l \to \nu_l) = 1 - \frac{1}{2}\sin^2 2\theta \left(1 - \cos 2.53\Delta m^2 \frac{L}{E}\right) \tag{107}$$

where L is the distance in m , $E \simeq p$ is the neutrino energy in MeV and Δm^2 is neutrino mass squared difference in eV^2. Thus, the transition probability is the periodical function of the parameter L/E .

Let us consider the $\nu_\mu \to \nu_\tau$ transitions and assume that $\sin^2 2\theta = 1$ (maximal mixing). The $\nu_\mu \to \nu_\mu$ survival probability is equal to one at the points $(\frac{L}{E})_1 = \frac{\pi}{2.53\Delta m^2} 2n$ $(n = 0, 1, 2\ldots)$, and we will find at these points only ν_μ. At the values $(\frac{L}{E})_2 = \frac{\pi}{2.53\Delta m^2}(2n+1)$ the survival probability is equal to zero, and only the ν_τ will be found at these points. At all other values of L/E we will find ν_μ *and* ν_τ. It is obvious that the sum of probabilities to find ν_μ and ν_τ is equal to one.

The phenomena we have described is called *neutrino oscillations* . In order to observe neutrino oscillations it is necessary that the mixing angle is large enough and the parameter Δm^2 satisfies the following condition

$$\Delta m^2 \geq \frac{E}{L} \tag{108}$$

The sensitivities to the parameter Δm^2 of neutrino experiments at different facilities are quite different and cover a very broad range of values of Δm^2. The experiments with accelerator neutrinos have sensitivities to the parameter Δm^2 in the range $10 - 10^{-3}$ eV^2, the experiments with the reactor neutrinos in the range $10^{-2} - 10^{-3}$ eV^2, the experiments with the atmospheric neutrinos in the range $10^{-1} - 10^{-4}$ eV^2 and finally experiments with the solar neutrinos have sensitivity to the parameter Δm^2 down to $10^{-10} - 10^{-11}$ eV^2

It is convenient to introduce the neutrino oscillation length

$$L_0 = 4\pi \frac{E}{\Delta m^2} \tag{109}$$

For the the transition probability we have

$$\mathrm{P}(\nu_l \to \nu_{l'}) = \frac{1}{2}\sin^2 2\theta \left(1 - \cos 2\pi \frac{L}{L_0}\right) \qquad (l \neq l'). \tag{110}$$

The expression for the oscillation length can be written in the form

$$L_0 = 2.47 \frac{E(\mathrm{MeV})}{\Delta m^2(\mathrm{eV}^2)}\,\mathrm{m} \tag{111}$$

Neutrino oscillations can not be observed if the oscillation length is much larger than the distance L between the neutrino source and the neutrino detector. In order to observe neutrino oscillations, oscillation length must be smaller or of the order of magnitude of L.

Reaction	Maximal energy (MeV)	Standard Solar Model flux ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)
$p\,p \to d\,e^{+}\,\nu_e$	≤ 0.42	6.0×10^{10}
$e^{-}\,{}^{7}\mathrm{Be} \to \nu_e\,{}^{7}\mathrm{Li}$	0.86	4.9×10^{9}
${}^{8}\mathrm{B} \to {}^{8}\mathrm{Be}\,e^{+}\,\nu_e$	≤ 15	5.0×10^{6}

Table 3: Main sources of solar ν_e' s.

Let us notice that for the comparison of neutrino oscillation theory with experimental data it is necessary to average the corresponding theoretical expression for transition probabilities over the neutrino energy spectrum, the region where neutrinos were produced and so on. As a result of such averaging, the cosine term in the expressions (107) usually disappears.

16 Experiments on the search for neutrino oscillations

There are at present data of numerous experiments on the search for neutrino oscillations. The important indications in favor of the neutrino masses and mixing were found in the solar neutrino experiments. The compelling evidence in favor of neutrino oscillations was obtained recently in the Super-Kamiokande atmospheric neutrino experiment. Some indications in favor of $\nu_\mu \to \nu_e$ oscillations were found also in the Los Alamos accelerator neutrino experiment. In many experiments with accelerator and reactor neutrinos no indications in favor of neutrino oscillations were found. We will first discuss the solar neutrino experiments.

16.1 The solar neutrino experiments

The energy of the sun is generated in the reactions of the thermonuclear *pp* and CNO cycles. From the thermodynamical point of view the energy of the sun is produced in the transition of four protons and two electrons into ${}^{4}He$ and two neutrinos

$$4\,p + 2\,e^{-} \to {}^{4}\mathrm{He} + 2\,\nu_e\,, \tag{112}$$

Thus, the generation of energy of the sun is *accompanied by the emission of electron neutrinos*

The main sources of solar neutrinos are the reactions that are listed in Table 3. In this table the maximal neutrino energies and neutrino fluxes, predicted by the Standard Solar Model (SSM), are also given.

As it seen from Table 3, solar neutrinos are mainly low energy *pp* neutrinos. According to SSM the flux of the medium energy monochromatic ^7Be neutrinos is about 10 % of the total flux. The flux of the high energy ^8B neutrinos is only about 10^{-2} % of the total flux. The ^8B neutrinos give, however, the main contribution to the event rates of experiments with high energy threshold.

The results of the five underground solar neutrino experiments are available at present. In the pioneering radiochemical experiment by R. Davis et al (Homestake mine, USA), a tank filled with 615 tons of C_2Cl_4 liquid is used as a target. Solar neutrinos are detected in this experiment by a radiochemical method, proposed by B.Pontecorvo in 1946, through the observation of the reaction

$$\nu_e + {}^{37}\mathrm{Cl} \to e^- + {}^{37}\mathrm{Ar} \tag{113}$$

The radioactive atoms of ^{37}Ar are extracted from the tank by purging it with ^4He gas. The atoms of ^{37}Ar are placed in a low background proportional counter in which the process

$$e^- + {}^{37}\mathrm{Ar} \to \nu_e + {}^{37}\mathrm{Cl} \tag{114}$$

is observed by the detection the Auger electrons (electrons of conversion).

After 2 months of exposition about 16 atoms of the ^{37} Ar are extracted from the volume that contains 2.2×10^{30} atoms of ^{37}Cl!

The solar neutrinos have been observed in the Davis experiment for about 30 years. For the observed event rate Q_{Cl}, averaged over 108 runs, the following value was obtained

$$Q_{\mathrm{Cl}} = 2.56 \pm 0.16 \pm 0.16 \quad \mathrm{SNU} \tag{115}$$

where 1 SNU = 10^{-36} events/atom s. The observed event rate is about three times less than the rate predicted by the SSM

$$(Q_{Cl})_{SSM} = 7.7 \pm 1.2 \quad \mathrm{SNU} \tag{116}$$

The minimal neutrino energy at which the process (113) become possible (the threshold of the process) is equal to $E_{th} = 0.81$ MeV. Thus, the low energy *pp* neutrinos are not detected in the Davis experiment. The most important contribution to the event rate comes from the high energy ^8B neutrinos. About 15% of the events are due to ^7Be neutrinos.

In the radiochemical GALLEX (Italy) and SAGE (Russia) experiments the solar ν_e's are detected through the observation of the reaction

$$\nu_e + {}^{71}\mathrm{Ga} \to e^- + {}^{71}\mathrm{Ge} \tag{117}$$

In the GALLEX experiment the target is a tank with 30.3 tons of the ^{71}Ga in the gallium-chloride solution. In the SAGE experiment a metallic ^{71}Ga target is used (57 tons of ^{71}Ga).

The threshold of the process (117) is $E_{th} = 0.23$MeV. Thus, neutrinos from all solar neutrino reactions are detected in these experiments (according to the

SSM the contributions of the pp , ^{7}Be and ^{8}B neutrinos to the event rate in the gallium experiments are about 54 %, 27% and 10%, respectively). The event rates obtained in the GALLEX and SAGE experiments are equal

$$\begin{aligned} Q_{\rm Ga} &= 77.5 \pm 6.2^{+4.3}_{-4.7} \quad \text{SNU} \quad \text{(GALLEX)} \\ Q_{\rm Ga} &= 66.6 \pm {}^{+6.8}_{-7.1} {}^{+3.8}_{-4.0} \quad \text{SNU} \quad \text{(SAGE)} \end{aligned} \tag{118}$$

The predicted rate is about two times larger than the observed rates

$$(Q_{\rm Ga})_{\rm SSM} = 129 \pm 8 \quad \text{SNU} \tag{119}$$

In the Kamiokande and Super-Kamiokande experiments (Japan) the solar neutrinos are detected through the observation of the process

$$\nu + e \to \nu + e \tag{120}$$

In the Super-Kamiokande experiment a large 50 ktons water-Cerenkov detector is used. The inner surface of the detector is covered with 11146 large photomultipliers in which the Cerenkov light from the recoil electrons is detected. About 14 neutrino events per day are observed by the Super-Kamiokande experiment (in the previous Kamiokande experiment one neutrino event per day was detected). At high energies the direction of the momentum of the recoil electrons is practically the same as the direction of the momentum of the neutrinos. Thus, the measurement of the direction of the momenta of the electrons allows one to detect events induced by neutrinos coming from the sun. The recoil electron energy threshold is rather large (7 MeV in the Kamiokande experiment and 5.5 MeV in the Super-Kamiokande experiment). Thus, only the ^8B neutrinos are detected in these experiments. From the results of the Kamiokande and Super-Kamiokande experiments the following values of the solar neutrinos fluxes were obtained, respectively

$$\begin{aligned} \Phi &= (2.80 \pm 0.19 \pm 0.33)\ 10^6 \text{cm}^{-2}\text{s}^{-1} \\ \Phi &= (2.44 \pm 0.05^{+0.09}_{-0.07})\ 10^6 \text{cm}^{-2}\text{s}^{-1} \end{aligned} \tag{121}$$

The measured fluxes are about 1/2 of the predicted one by the SSM

$$\Phi_{\rm SSM} = (5.15^{+1.00}_{-0.72})\ 10^6 \text{cm}^{-2}\text{s}^{-1} \tag{122}$$

Thus, from the results of all solar neutrino experiments it follows that the fluxes of the solar ν_e's on the earth in different ranges of energies are significantly smaller than the predicted fluxes. This deficit constitutes *the solar neutrino problem.*

Neutrino oscillations is the most plausible explanation of the solar neutrino problem. If neutrinos are massive and mixed, the solar ν_e's on the way to the earth can be transfered into other neutrinos (ν_μ and/or ν_τ). However, in the chlorine and gallium experiments only ν_e's can be detected. The muon and/or tau neutrinos give some contribution to the event rates of the Kamiokande and the Super-Kamiokande experiments. However, cross section of $\nu_\mu(\nu_\tau) - e$ scattering is about 1/6 of the cross section of $\nu_e - e$ scattering, and therefore, the main contribution to the event rate of these experiments also comes from ν_e's. Thus, if there are neutrino oscillations, the event rates detected in the solar neutrino experiments will be less than the expected ones.

Solar neutrinos, produced in the central zone of the sun, on their way to the earth pass through a large amount of matter of the sun. At some values of the mixing parameters effects of the coherent interactions of neutrinos with matter can enhance significantly the probability of the transition of solar ν_e's into other states.

The refraction index of the neutrinos in matter depends on the amplitude of elastic scattering of neutrinos in the forward direction. Both the CC and NC interactions give contribution to the amplitude of elastic $\nu_e - e$ scattering. The amplitude of the elastic $\nu_\mu(\nu_\tau) - e$ scattering is determined only by the NC interaction. Thus, the refraction indexes of the ν_e and $\nu_\mu(\nu_\tau)$ are different. Hence, when a neutrino wave propagates through matter, the flavor content of the neutrino state is changing. Under the condition

$$\Delta m^2 \cos 2\theta = 2\sqrt{2}\mathrm{G_F}\rho_\mathrm{e}\mathrm{E} \tag{123}$$

where ρ_e is the electron number-density, the combined effect of neutrino masses and mixing and coherent neutrino interaction in matter can enhance significantly the probability of the transition of ν_e's into other states. This is so-called Mikheev-Smirnov-Wolfenstein effect (MSW). In the sun matter MSW effect can be important if $10^{-7} \leq \Delta m^2 \leq 10^{-4} eV^2$.

All existing solar neutrino data can be described, if we assume that there is mixing of two neutrinos and the values of the solar neutrino fluxes are given by the SSM. In such a case there are only two free parameters: Δm^2 and $\sin^2 2\theta$. From the fit of the events rates, measured in all solar neutrino experiments, there were found two MSW fits with large and small mixing angle (correspondingly, LMA and SMA)

$$10^{-5} < \Delta m^2 < 10^{-4}\mathrm{eV}^2 \quad 0.8 < \sin^2 2\theta < 1$$

$$10^{-5} < \Delta m^2 < 6 \cdot 10^{-6}\mathrm{eV}^2 \quad 4 \cdot 10^{-3} < \sin^2 2\theta < 10^{-2}$$

The events rates measured in all solar neutrino experiments can be also described by vacuum oscillations (VO) with

$$8 \cdot 10^{-11} < \Delta m^2 < 4 \cdot 10^{-10}\mathrm{eV}^2 \quad 0.6 < \sin^2 2\theta < 1$$

In the high-statistics Super-Kamiokande experiment the spectrum of the recoil electrons in the process $\nu + e \to \nu + e$ was measured. If there are no oscillations this spectrum can be predicted in a model-independent way. This is connected with the fact that in the Super-Kamiokande experiment only neutrinos from ^8B decay, the spectrum of which is determined by the weak interactions, are measured. No sizable distortion of the spectrum was observed in this experiment.

In the Super-Kamiokande experiment the day-night asymmetry was also measured. During night neutrinos pass through the earth and the measurement of the day-night asymmetry allows in a model-independent way to measure matter effects. No significant day-night asymmetry was observed:

$$\frac{N-D}{(N+D)/2} = 0.034 \pm 0.022 \pm 0.013$$

These new measurements allows one to constrain the possible values of the neutrino oscillation parameters. From the fit of all solar neutrino data it follows that the most favored fit is the LMA one with

$$6 \cdot 10^{-5} < \Delta m^2 < 3 \cdot 10^{-4} \mathrm{eV}^2 \quad 0.8 < \sin^2 2\theta < 1$$

If solar neutrino fluxes from different sources are considered as free parameters and it is assumed that the ν_e transition probability is equal to one in this case from the analysis of the data of different solar neutrino experiments it follows that the flux of ^8Be neutrinos must be strongly suppressed. This consequence of the general analysis of existing solar neutrino data will be checked in the future BOREXINO experiment that is planned to start in 2002 in the underground Laboratory Gran Sasso (Italy). In this experiment mainly medium energy ^8Be neutrinos will be detected through the observation of the $\nu - e$ scattering in a scintillator.

In the SNO experiment (Sudbury Neutrino Observatory, Canada) the solar ν_e's are detected through the observation of electrons in the CC reaction

$$\nu_e + d \to e^- + p + p \tag{124}$$

In the nearest future in the SNO experiment the solar neutrinos will be detected also through the observation of the neutrons from the NC process

$$\nu + d \to \nu + n + p \tag{125}$$

Not only ν_e's but also ν_μ's and ν_τ's will be detected by this method. The comparison of the NC and CC data will allow one to obtain a model-independent information on the transitions of the solar ν_e's into other neutrino states.

16.2 The atmospheric neutrino experiments

The most compelling evidence in favor of neutrino oscillations was obtained recently by the atmospheric neutrino experiments. The main source of atmospheric neutrinos is the following chain of the decays

$$\pi \to \mu + \nu_\mu, \qquad \mu \to e + \nu_e + \nu_\mu, \tag{126}$$

the pions being produced in the interaction of cosmic rays with nuclei in the earth's atmosphere. At relatively small energies (≤ 1 GeV) the ratio of the muon and electron neutrinos is equal to 2. At higher energies this ratio becomes larger than 2 (not all muons have enough time to decay in the atmosphere). The ratio can be predicted, however, with the accuracy better than 5 %. The absolute fluxes of the electron and muon neutrinos are predicted at present with accuracy 25-30 %. The results of the atmospheric neutrino experiments are usually presented in the form of the double ratio R of the ratio of the observed muon and electron events to the ratio of the muon and electron events calculated by Monte Carlo method under the assumption that there are no neutrino oscillations. In all latest atmospheric neutrino experiments it was found that the ratio R is significantly smaller than one:

$$\begin{aligned} R &= 0.65 \pm 0.05 \pm 0.08 \qquad \text{(Kamiokande)} \\ R &= 0.54 \pm 0.05 \pm 0.11 \qquad \text{(IMB)} \\ R &= 0.61 \pm 0.15 \pm 0.05 \qquad \text{(Soudan2)} \\ R &= 0.638 \pm 0.017 \pm 0.050 \qquad (\mathrm{Super-Kamiokande}) \end{aligned} \tag{127}$$

The fact that the double ratio R is less than one is a model-independent indication in favor of the disappearance of ν_μ (or appearance of ν_e).

Compelling evidence in favor of the disappearance of ν_μ was obtained recently by the Super-Kamiokande experiment. In this experiment a significant zenith angle dependence of the number of high-energy muon events was found (the zenith angle θ is the angle between the vertical direction and the neutrino momentum). The angle θ is connected with the distance that neutrinos pass from the production region to the detector. Down-going neutrinos ($\cos\theta = 1$) pass a distance of about 20 km. The distance that up-going neutrinos ($\cos\theta = -1$) travel is about 13000 km.

The possible source of the zenith angle dependence of the numbers of atmospheric neutrino events is the magnetic field of the earth. However, at energies larger than 1 GeV the effect of the magnetic field of the earth is small and the numbers of down-going and up-going ν_μ (ν_e) must be equal.

The Super-Kamiokande collaboration observed the significant up-down asymmetry of the muon events:

$$A_\mu = \frac{U - D}{U + D} = -0.311 \pm 0.043 \pm 0.010 \tag{128}$$

Here U is the total number of up-going muons and D is the total number of down-going muons.

For the up-down asymmetry of the electron events a value compatible with zero was found:

$$A_e = 0.036 \pm 0.067 \pm 0.02 \tag{129}$$

The data that was obtained by the Super-Kamiokande collaboration can be explained by $\nu_\mu \to \nu_\tau$ neutrino oscillations. From the analysis of the data for the parameters Δm^2 and $\sin^2 2\theta$ the following best-fit values were obtained

$$\Delta m^2 = 2.5 \cdot 10^{-3}\mathrm{eV}^2, \qquad \sin^2 2\theta = 1 \tag{130}$$

The disappearance of the up-going muon neutrinos is due to the fact that these neutrinos travel longer distance than the down-going muon neutrinos and have more time to transfer into ν_τ.

The ν_μ survival probability depends on the ratio L/E and is given by the expression

$$\mathrm{P}(\nu_\mu \to \nu_\mu) = 1 - \frac{1}{2}\sin^2 2\theta \left(1 - \cos\, 2.54\Delta m^2 \frac{L}{E}\right) \tag{131}$$

At $L/E \geq 10^3$km/GeV the argument of the cosine in the expression (131) is large and the cosine in this expression disappears due to averaging over the neutrino energies and distances. As a result at $L/E \geq 10^3 km/GeV$ for the averaged survival probability we have $\bar{\mathrm{P}}(\nu_\mu \to \nu_\mu) = 1 - \frac{1}{2}\sin^2 2\theta \simeq \frac{1}{2}$

The atmospheric neutrino range $\Delta m^2 \simeq 10^{-3} eV^2$ will be probed the long-baseline (LBL) accelerator neutrino experiments. The first LBL experiment K2K have started in Japan in 1999. The distance between the source (accelerator) and the detector (Super-Kamiokande) is about 250 km. Two other LBL experiments are under preparation. In the MINOS experiment neutrinos produced from the accelerator at Fermilab (USA) will be detected by the detector in the Soudan mine (the distance is about 730 km). In another LBL experiment neutrinos produced from the accelerator at CERN (Geneva) will be detected by the detector at the underground Laboratory Gran Sasso (Italy) (the distance is also about 730 km). In the accelerator experiments initial neutrinos are mainly ν_μ with a small admixture of ν_e. In the CERN-Gran Sasso experiment appearance of ν_τ will be searched for.

16.3 The LSND experiment

Some indications in favor of $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations were obtained also in the short-baseline experiment that was done at the Los Alamos linear accelerator (USA). In this experiment a beam of pions produced by 800 MeV protons hits a copper target. In this target the π^+-mesons come to rest and decay ($\pi^+ \to \mu^+ + \nu_\mu$). The produced muons also come to rest in the target and decay ($\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$). Thus, in decays of the π^+'s and μ^+'s muon neutrinos ν_μ, muon antineutrinos $\bar{\nu}_\mu$ and electron neutrinos ν_e are produced. There is no electron antineutrinos $\bar{\nu}_e$ from these decays . Let us notice that $\bar{\nu}_e$'s are produced in the decay chain that starts with π^-'s. However, practically all π^-'s are captured by nuclei in the target and have no time to decay.

In the LSND neutrino detector at a distance of about 30 m from the target, the electron antineutrinos $\bar{\nu}_e$'s were searched for through the observation of the classical process

$$\overline{\nu}_e + p \to e^+ + n \tag{132}$$

In the interval of the positron energies $30 < E < 60$ MeV it was observed in the LSND experiment $87.9 \pm 22.4 \pm 6.0$ events.

The observed signal can be explained by $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations. If we take into account the results of the other short-baseline experiments in which neutrino oscillations were not found, from the LSND experiment the following ranges of the oscillation parameters can be found

$$0.2 \leq \Delta m^2 \leq 1\mathrm{eV}^2 \qquad 2 \cdot 10^{-3} \leq \sin^2 2\theta \leq 4 \cdot 10^{-2} \tag{133}$$

The indications in favor of $\nu_\mu \to \nu_e$ oscillations, obtained in the LSND experiment, will be checked by the BOONE experiment (Fermilab, USA) that will start in 2002.

17 Neutrinoless double β-decay

We have discussed in the previous sections neutrino oscillation experiments that allow to obtain information on a very small neutrino mass squared differences. Important information on the neutrino masses and *the nature of massive neutrinos* can be obtained from experiments on the investigation of neutrinoless double β-decay

$$(A, Z) \to (A, Z + 2) + e^- + e^- \tag{134}$$

Here (A, Z) is some even-even nucleus. In the experiments neutrinoless double β-decay of ^{76}Ge, ^{136}Xe, ^{130}Te, ^{100}Mo and other nuclei are searched for. The process (134) is allowed, if the total lepton number L is not conserved, i.e. if massive neutrinos are Majorana particles.

In the framework of the standard CC weak interaction with Majorana neutrino mixing neutrinoless double β-decay is second order in the Fermi constant G_F process with a virtual neutrino. The matrix element of the process is proportional to the effective Majorana mass

$$\langle m \rangle = \sum_i U_{ei}^2 m_i \tag{135}$$

where m_i is the neutrino mass.

There are many experiments in which neutrinoless double β-decay of different nuclei are searched for. No positive indications in favor of such decay were found up to now. A very stringent lower bound on the life-time was obtained in the Heidelberg-Moscow experiment in which the neutrinoless double β-decay of the ^{76}Ge was search for:

$$T_{1/2} > 1.6 \times 10^{25}\,\mathrm{years} \tag{136}$$

The upper bound of the effective Majorana mass that can be obtained from this result depends on the calculation of nuclear matrix elements. Using different calculations one can find

$$|\langle m \rangle| > (0.3 - 0.9) \text{ eV} \tag{137}$$

In the next generation experiments on the search for neutrinoless double β-decay the sensitivity $|\langle m \rangle| \simeq 10^{-1}$ eV will be achieved (NEMO3, Heidelberg-Moscow,IGEX). The possibility of the experiments, in which the sensitivity $|\langle m \rangle| \simeq 10^{-2}$ eV will be reached, is under investigation.

18 Neutrino masses from experiments on the measurement of the β-spectrum of tritium

The first method of measuring neutrino mass was proposed in the classical paper by Fermi on the β-decay. The method consists in the precise measurement of the end-point part of the β-spectrum, the part of the spectrum that is most sensitive to the small neutrino mass.

Usually, for the determination of neutrino mass by this method the β-spectrum of the decay of the tritium

$$^3\mathrm{H} \to {}^3\mathrm{He} + \mathrm{e}^- + \bar{\nu}_\mathrm{e} \tag{138}$$

is investigated. The β-spectrum of this decay is determined by the phase-space factor

$$\frac{dN}{dT} = C\, pE(Q-T)\sqrt{(Q-T)^2 - m_\nu^2}F(E) \tag{139}$$

Here p and E are the electron momentum and energy, respectively, $T = E - m_e$ is the electron kinetic energy, $Q \simeq 18.6$ keV is the energy release, $C = const$, $F(E)$ is the known function that describes the Coulomb interaction of the final particles and m_ν is the mass of the ν_e. If the neutrino mass is equal to zero, $T_{max} = Q$. For nonzero neutrino mass $T_{max} = Q - m_\nu$. Thus, for nonzero neutrino mass at the end-point part of the electron spectrum the deficit of the events (with respect to the number of the events expected for $m_\nu = 0$) must be observed.

At the moment no positive indications in favor of nonzero neutrino mass were obtained from the ^{3}H experiments. For the upper bound of the neutrino mass it was found

$$\begin{array}{ll} m_\nu \leq 2.5 \ \text{ eV} & \text{(Troitsk)} \\ m_\nu \leq 2.2 \ \text{ eV} & \text{(Mainz)} \end{array} \tag{140}$$

In future experiments on the measurement of the end-point part of the spectrum of β-decay of ^3H the sensitivity $m_\nu \simeq 0.5$ eV is planned to be achieved.

19 Conclusion

The neutrinos play very a important role in particle physics and astrophysics. They have enormous penetration properties and they give us a unique possibility to investigate the internal structure of the nucleon, the internal invisible region of the sun where solar energy is produced etc.

The neutrinos are exceptional particles as for their internal properties. The neutrino masses are many orders of magnitude smaller than the masses of their family partners (electron, muon, tau). Because of the smallness of the neutrino masses new physical phenomenon, *neutrino oscillations*, the periodical transitions between different flavor neutrinos in the vacuum or in matter, becomes possible. The evidence for this phenomenon, that was predicted many years ago, was obtained recently by the Super-Kamiokande collaboration in Japan. The investigation of the neutrino oscillations that is going on all over the world is a new field of research in particle physics and astrophysics.

The investigation of the neutrino oscillations, neutrinoless double β-decay, β-spectrum of ^3H-decay and other effects will allow us to obtain important information on the neutrino masses, element of the neutrino mixing matrix and the nature of massive neutrinos (Dirac or Majorana?).

The exceptional smallness of the neutrino masses requires a special explanation. There is a general belief that small neutrino masses are generated by new interactions beyond the Standard Model. One of the plausible explanation of the small neutrino masses is connected with a violation of the lepton number at a mass scale that is much larger than the scale of the violation of electroweak symmetry $M_{EW} \simeq 10^2$ GeV that determine masses of the leptons, quarks and $W^{\pm}$, Z^0 bosons. If this explanation is correct the massive neutrinos are truly neutral Majorana particles. All other fundamental fermions (leptons and quarks) are charged Dirac particles.

It is a pleasure for me to thank Tommy Ohlsson for careful reading of the paper and useful discussions and Michael Ratz for the help in the preparation of the figures.

References

[1] J.N. Bahcall, *Neutrino Physics and Astrophysics*, Cambridge University Press, 1989.

[2] V. Barger, *Neutrino masses and Mixing at the Millenium*, hep-ph/0003212.

[3] S.M. Bilenky and B. Pontecorvo, Phys. Rep. **41**, 225 (1978).

[4] S.M. Bilenky and S.T. Petcov. Rev. Mod, Phys, 59, 671 (1989).

[5] S.M. Bilenky, C. Giunti and W. Grimus, Progr. in Part. and Nucl. Phys. **43**, 1 (1999).

[6] F. Boehm and P. Vogel, *Physics of Massive Neutrinos*, Cambridge University Press, Cambridge, 1994.

[7] J. Brunner, Fortsh. Phys. **45**, 343 (1997)

[8] W. Haxton, B. Holstein, *Neutrino Physics*, Am. J. Phys. **68**,15 (2000).

[9] B. Kayser, F. Gibrat-Debu and Perrier, *The Physics of Massive Neutrinos*, World Scientific Singapore, 1989.

[10] C.W. Kim and A. Pevsner, *Neutrinos in Physics and Astrophysics*, Contemporary Concepts in Physics, Vol. 8, Harwood Academic Press, Chur, Switzerland, 1993.

[11] R.N. Mohapatra and P.B. Pal, *Massive Neutrinos in Physics and Astrophysics*, World Scientific, Singapore, 1998.

[12] *Neutrino Physics*, 2th edition, editor K. Winter, Cambridge University Press, Cambridge, 2000.

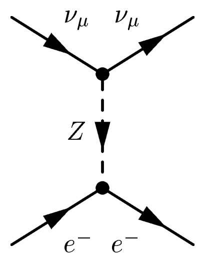
[13] L. Oberauer and F. von Feilitzsch, Rept. Prog. Phys. **55**, 1093 (1992).

[14] A. Pais *Inward bound: of Matter and Forces in the Physical World*, Oxford University Press, 1986.

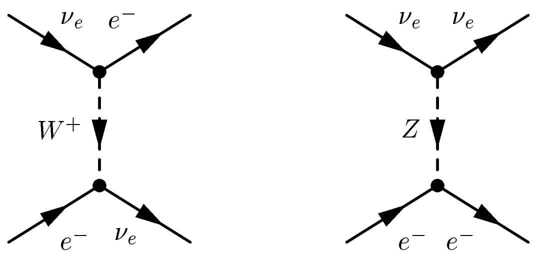
[15] D.H. Perkins, *Introduction to high Energy Physics*, 4th edition, Cambridge University Press, Cambridge, 2000.

[16] P. Renton *Electroweak Interactions - An Introduction to the Physics of Quarks and Leptons*, Cambridge, Cambridge University Press, 1990.

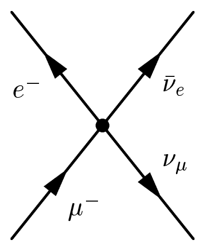
[17] K. Zuber, Phys. Rep. **305**, 295 (1998).

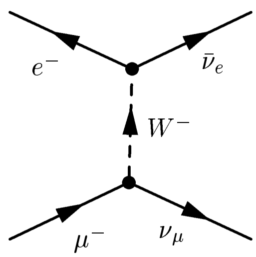


ν_μ
ν_μ
Z
e^-
e^-

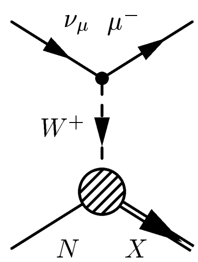


ν_e
e^-
W^+
e^-
ν_e
ν_e
ν_e
Z
e^-
e^-


e^-
$\bar{\nu}_e$
ν_μ
μ^-



e^-
$\bar{\nu}_e$
W^-
μ^-
ν_μ


ν_μ
μ^-
W^+
N
X